

STIRLING COMMERCIALIZATION STUDY
FINAL REPORT

Volume II

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APPENDIX A

LANGUAGE FROM HOUSE REPORT 101-226

ACCOMPANYING HR 1759,

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MULTIYEAR AUTHORIZATION ACT OF 1989.

Committee View

Management of the Stirling Engine Program

The Stirling engine may eventually contribute to a long-term solution to the nation's emission problems and represents a strategic alternative for pollution abatement. Research and development in Stirling technology suggest the logical next step for the Stirling is a commercial demonstration of the engine which would place into the hands of end-users multiple Stirling units for field tests. Supporters of the Stirling engine have proposed a government and industry cost-sharing demonstration program.

For the last decade, the federal government has funded a Stirling engine research, development, and demonstration program, with DOE providing \$130 million and NASA only \$0.9 million. Because of its expertise in combustion technology, NASA managed the Stirling program on behalf of DOE. There is a strong consensus that the automotive Stirling engine has matured beyond the R&D stage. Therefore, DOE has decided to terminate its Stirling engine R&D program and has not requested any funding for it in FY 1990.

For the last 4 years, NASA has funded a \$900,000, 3-vehicle demonstration program. It has been suggested that full sponsorship of the Stirling engine program be transferred from DOE to NASA. The Committee is uncertain whether transferring agency sponsorship would be in the best interests of Stirling engine development and commercialization.

To determine the optimal long-term sponsor for the Stirling engine, the Committee directs NASA to participate in an interagency study including the Department of Energy, the EPA, and the Air Force, in consultation with other interested agencies, to evaluate potential sponsorship of such a program. The study should include the optimal size and scope of the demonstration fleet, a determination of the private sector contribution, and a mechanism for securing such funds. The Committee encourages NASA to consult with the private sector in developing the study plan. The study should be submitted to the Congress by February 1, 1990.

APPENDIX B

DEFINITIONS

Stirling engine - Any closed-cycle, externally heated, hot-gas engine employing regenerative heating. Theoretically, the Stirling engine cycle provides the maximum cycle efficiency achievable in an engine. (For an explanation of the basic Stirling cycle please, see appendix F.)

Kinematic Stirling engine - Any Stirling engine employing a mechanical device, such as a crank or swashplate, to convert reciprocating power from a piston to rotary shaft power to drive a device such as an electric generator pump or a vehicle.

Free-piston Stirling - Any Stirling engine in which a power output device such as an electric generator, a hydraulic pump, or a compressor is incorporated directly into the engine. No mechanical device is employed to convert the reciprocating piston power to rotary shaft power.

Mod I ASE - The first-generation, experimental, kinematic Stirling engine designed and built in the DOE Automotive Stirling Engine (ASE) Program.

Mod II ASE - The second-generation, proof-of-concept, kinematic Stirling engine designed and built in the DOE ASE program and intended to demonstrate achievement of the DOE program goals.

APPENDIX C

DEPARTMENT OF ENERGY
AUTOMOTIVE STIRLING ENGINE PROGRAM
CHRONOLOGY

February 1978	Public Law 95-238, Title III (The Automotive Stirling Engine Program evolved from this legislation.)
March 1978	Contract DEN3-32 awarded to MTI.
May 1980	Final Mod I ASE design review conducted.
January 1981	First Mod I ASE hot engine test performed.
April 1981	First Mod I ASE Stirling engine system test performed.
August 1981	Mod I ASE engine is fully characterized.
May 1982	First Mod I ASE is installed in vehicle.
July 1982	First USA-built Mod I ASE begins test.
April 1983	First upgraded Mod I ASE begins test.
May 1983	Reference engine radically redesigned and Mod II ASE design begun.
May 1984	Mod I ASE in Spirit vehicle tested by GM Research Laboratories as part of ITEP.
September/ October 1984	Mod I ASE evaluated by Deere as part of ITEP.
April 1985	Mod II ASE basic engine design review conducted.
August 1985	Mod II ASE engine system design review conducted.
September 1986	Mod I ASE in Air Force multistop van delivered to Langley AFB for phase I of NASA TU demonstration. Completed August 1987.
July 1986	Mod II ASE begins testing.
September 1987	Mod I ASE in Air Force D-150 pickup truck delivered to Langley AFB for phase II of NASA TU demonstration. Completed August 1988.
February 1988	First Mod II ASE is fully characterized.
May 1988	Mod II ASE installation in USPS LLV completed.
September 1989	Mod II ASE in USPS LLV is delivered to Merrifield, Virginia, for phase III of NASA TU demonstration. Completed December 1989.
December 1989	Contract DEN 3-32 is concluded.

APPENDIX D

EMISSIONS AND FUEL ECONOMY

Current interest in our overall environment has caused an ongoing evaluation of automotive emissions and fuel economy standards by the Government and environmental groups that has resulted in the automotive industry making conventional engines cleaner and more efficient. As a consequence, the baselines in both emissions and fuel economy standards and regulations are changing. Also, more stringent emissions regulations are being proposed for all powerplants including truck (light duty and heavy duty) and off-highway and stationary applications. It would be reasonable to expect that in the future all light trucks, vans and pickups would have to adhere to the same stringent emission standards similar to those imposed for passenger cars. Further, stricter regulations are being created for unique geographical locations where special conditions exist, such as the ozone formation (ref. D-1) within confined air basins such as California and high carbon monoxide (CO) levels (ref. D-2) in areas that combine cold weather and high altitude such as Denver, Colorado. Also, additional improvements in fuel economy will reduce emissions of carbon dioxide (CO₂), a gas which may cause global warming. It should be noted that, current and proposed automotive emissions and corporate average fuel economy (CAFE) standards are traditionally examined separately rather than together as associated standards that influence each other.

Current automotive exhaust emissions standards established by the Federal Government and the State of California are listed in table V. The Federal standard for unburned hydrocarbons is based on the total hydrocarbon content of the exhaust; the California standard includes all hydrocarbon constituents except methane. The California standards for nonmethane HC and CO will be lowered, as shown, in 1993. The Federal standard also includes a limit of 0.6 g/mile on exhaust particulates. The corresponding exhaust particulate limit in California is 0.08 g/mile. Three different proposals for Federal automotive emissions standards are presented in table VI (from ref. D-3).

A significant amount of research and development funds are being spent by the automotive industry and engine manufacturers to meet the current and future EPA

TABLE V - CURRENT AUTOMOTIVE EMISSIONS STANDARDS

Emissions standard	Total HC	Nonmethane HC	CO	NO _x
	Gaseous exhaust emissions, g/mile			
Federal	0.41	--	3.4	1.0
California	--	0.39	7.0	0.4
	--	^a 0.25	^a 3.4	

^a Nonmethane HC and CO standards would be reduced to these limits in 1993.

and California Air Resources Board (CARB) regulated emissions standards (ref. D-4) and Federal CAFE requirements (ref. D-5). Most of these resources are directed at changes to conventional powerplants that are currently in production. More stringent emissions and fuel economy standards are being phased in to allow time for the industry to modify and verify the conventional engine. The lowest proposed Federal exhaust emissions levels for the gasoline-fueled passenger car are 1.7 g/mile for CO, 0.2 g/mile for NO_x, 0.125 g/mile for total hydrocarbons, and 0.08 g/mile for particulates. In addition to tailpipe emissions, requirements are now being proposed for evaporative, refueling, and running loss emissions (ref. D-3).

Ultimately, any alternative powerplant proposed for a demonstration program must be designed and evaluated for the emissions and fuel economy standards of the future (not the phase-in procedure currently used for today's production engines) and for the time when it would be introduced into the marketplace. The emissions and fuel economy goals for an alternative powerplant proposed for demonstration today should certainly be directed to the year 2000 and beyond.

TABLE VI. - PROPOSED FEDERAL AUTOMOTIVE EMISSIONS STANDARDS

[from ref. D-3.]

	Useful life, years/thousand miles	Current standards	Recommended by Administration	Emissions, g/mile			
				Reported by House subcommittee		Reported by Senate subcommittee	
				Phase 1	Phase 2 (2004) ^b	Phase 1	Phase 2 (2003)
Emissions, g/mile							
Nonmethane HC	5/50 7/75 10/100	^a 0.36 --- ---	0.25 --- ---	0.25 .31 ---	--- --- 0.125	--- --- 0.25	--- --- ---
Total HC	5/50 7/75 10/100	0.41 --- ---	0.41 --- ---	--- --- ---	--- --- ---	--- --- 0.31	--- --- 0.125
CO	5/50 7/75 10/100	3.4 --- ---	3.4 --- ---	3.4 4.2 ---	--- --- 1.7	--- --- 3.4	--- --- 1.7
NO _x	5/50 10/100	1.0 ---	0.7 ---	0.4 ---	--- 0.2	--- 0.4	--- 0.2
Evaporative emissions		Some control	Better control	Better control	Better control	Better control	Better control
Running losses		No control	Control	Control	Control	Control	Control
Refueling emissions		No Federal control	Stage 2	Stage 2; onboard if safe	Stage 2; onboard	Stage 2 + onboard	Stage 2 + onboard
I/M		Basic	Enhanced	Enhanced	Enhanced	Enhanced	Enhanced
RVP (psi)		10.5	9.0	9.0	9.0	9.0	9.0
Emission Warranties		5/50 for defects, all parts	Same as current	Same as current	Same as current	Extended to 8/80 for catalyst and electronic control unit; reduced to 2/24 for all other parts	Extended to 8/80 for catalyst and electronic control unit; reduced to 2/24 for all other parts
Emission system diagnostics		No requirement intent to adopt something	Authority and something	EPA must adopt something	EPA must adopt something	EPA must adopt	EPA must adopt

^a Rough equivalent to actual total HC standard, for comparison with proposals.^b House Subcommittee phase 2 standards are subject to EPA study and revision, not to exceed phase 1 standards.

ASE EMISSIONS AND FUEL ECONOMY

The emissions and fuel economy data are presented for the Mod I ASE powered Dodge D-150 pickup truck shown in table VII and the Mod II ASE powered Grumman Long Life Vehicle (LLV) shown in table VIII. All the data presented were for vehicles evaluated at certified facilities and driven on the EPA urban/highway driving cycle.

A comparison is made in table VII for the 1987 Dodge D-150 pickup truck powered by the Mod I ASE (80 horsepower) and a by conventional spark-ignition engine

TABLE VII. - COMPARISON OF STIRLING (MOD I ASE) AND SPARK IGNITION (3.7 LITER) ENGINES IN THE D-150 PICKUP TRUCK FOR EXHAUST EMISSIONS AND FUEL ECONOMY.

Date of Evaluation Vehicle Description Engine Description	Emissions, g/mile			Mileage, miles/gal		
	HC	CO	NO _x	Urban	Highway	Combined
April, 1988 '87 D-150 - 4000 lb Mod I ASE	0.33	3.18	1.14	16.8	26.4	20.1
October, 1988 '87 D-150 - 4000 lb Mod I ASE	0.14	0.70	0.77	18.0	27.2	21.2
November, 1989 '87 D-150 - 4000 lb Mod I ASE	0.23	0.98	0.67	16.7	25.2	19.7
'87 EPA Data '87 D-150 SI, 3.7 liter (95 hp)	0.31	2.30	1.36	16.8	21.8	18.7
Current Federal Emissions Standards LDT - Class 2	0.8	10.0	1.7			
Current Federal Emissions Standards Automotive	0.41	3.4	1.0			

(3.7-liter Slant six, 95 horsepower). Also, shown are the current emission standards for the light duty truck (Class 2) and the current Federal standards for the automotive application. The data base for the experimental Mod I ASE is limited, although it appears to be representative of the Mod I ASE external combustion system. The Mod I ASE data meet the current Federal emission standards for the light duty truck (Class 2). It appears that the relatively poor emissions performance of the conventional Dodge pickup truck engine is due in part to the looser standards for LDTs, since the tighter automobile standards can easily be met by a vehicle of similar weight powered by a conventional gasoline engine (LeSabre). Notwithstanding, the data show a wide range for the individual emissions - suggesting that no conclusion can be reached. Fuel economy improvements for the Mod I ASE range from 5 to 14 percent in the combined urban/highway cycle, when compared to the conventional spark-ignition engine in the D-150.

A comparison of the Grumman Long Life Vehicle (LLV), otherwise known as the USPS delivery van, powered by the Mod II ASE (nominal 73 horsepower) and a conventional spark-ignition engine (2.5 liter, 92 horsepower) is shown in table VIII. Also shown are the current Federal emission standards for the light duty truck (Class 1) and the current Federal standard for the automotive application. The Mod II ASE was designed for the automotive application to demonstrate the DOE program goals for emissions and fuel economy (see page 9). Specifically, the Mod II ASE was to be installed in a 1985 GM Celebrity, however it was never installed and no data are available.

The data base for the proof-of-concept Mod II ASE is very limited, and while it appears that the CO and HC emissions standards can be met by the Mod II ASE, the data for NO_x is marginal at best for the Mod II ASE for the current and proposed Federal emission standards for the light duty truck (Class 1). As with the Mod I ASE, the Mod II ASE shows a wide range for the individual emissions. Fuel economy improvements for the Mod II ASE fell short in the urban cycle and improved in the highway cycle, resulting in a 2 - 5 percent combined fuel economy loss when compared to the conventional spark-ignition engine (with EPA data for the 1989/1990 model years) in the Grumman LLV. However, the Mod II ASE data for

TABLE VIII. - COMPARISON OF STIRLING (MOD II ASE) AND CONVENTIONAL SPARK IGNITION ENGINES FOR EXHAUST EMISSIONS AND FUEL ECONOMY.

Date of Evaluation Vehicle Description Engine Description	Emissions, g/mile			Mileage, miles/gal		
	HC	CO	NO _x	Urban	Highway	Combined
October, 1989 Grumman LLV - 3375 lb Mod II ASE	0.11	2.18	1.09	17.9	27.9	21.3
December, 1989 Grumman LLV - 3375 lb Mod II ASE	0.165	1.6	1.54	17.6	26.6	20.7
'89/'90 EPA Data Grumman LLV - 3625 lb SI, 2.5 liter (92 hp)	0.22	6.8	0.32	20.4	23.9	21.8
'89 EPA Data '89 Celebrity- 3125 lb SI, 2.5 liter (100 hp)	0.108	0.71	0.22	26.3	39.6	31.0
'89 EPA Data '89 LeSabre - 3625 lb SI, 3.8 liter (165 hp)	0.150	1.15	0.24	20.6	35.9	25.5
Current Federal Emissions Standards LDT - Class 1	0.8	10.0	1.2			
Current Federal Emissions Standards Automotive	0.41	3.4	1.0			

December 1989 contains an anomaly (engine flameout during the test run) and may not be representative of the Mod II ASE external combustion system. It should be noted that in 1989, MTI conducted back to back "on-the-road" tests in the Albany, New York area with a Mod II ASE and a spark ignition engine installed in Grumman LLVs. According to MTI, these fuel economy tests, resulted in a 13 percent combined fuel economy gain for the Mod II ASE in the "simulated" urban/highway combined cycle when compared with the conventional spark-ignition engine.

Although it may not be totally prudent to compare exhaust emissions from production vehicles with those from experimental or developmental vehicles, comparing EPA data (ref. D-6) indicates that the MTI's ASE powered vehicles have about the same level of total hydrocarbons and CO as the spark-ignition-powered vehicles but a somewhat higher NO_x emission level. In order to provide a rough benchmark with the limited data available from vehicles powered by the Mod II ASE, EPA data from a few production automobiles are presented in table VIII.

The test data for the Mod I ASE's powered vehicles shown in table VII were obtained with gasoline. Limited test results for the D-150 pickup truck have also been obtained with oxygenated fuel blends containing 11 percent methyl tertiary butyl ether (MTBE) in gasoline (refs. D-7 and D-8). The leaning effect of oxygenated fuel blends tends to reduce carbon monoxide emissions for vehicles with spark-ignition engines operating at cold-weather and high-altitude conditions. The limited CO emissions data comparing 11 percent MTBE fuel blends with gasoline do not appear to be conclusive: for some tests there were no significant differences; other tests indicated a somewhat lower CO level when the 11 percent MTBE fuel blend was used. The Mod I ASE emissions are penalized somewhat by the need for warmup periods (70 to 80 seconds prior to cold start and 20 to 30 seconds prior to hot start) in order to reach the required heater head operating temperature. The Mod I ASE emissions data from reference D-8 were obtained with an exhaust gas recirculation (EGR) ratio of 37 percent; the EGR used for the other Mod I ASE powered vehicle tests (refs. D-7 and D-9) is not known. Increasing EGR tends to reduce NO_x without affecting other emission products. An important consideration is that the production vehicles contain catalytic converters but the Stirling-engine-powered vehicles contain no catalytic converters.

The potential to attain acceptable vehicle performance, reliability, durability, and cost with various advanced powerplants and alternative fuels while meeting future emissions standards is discussed by Amann of GMRL (ref. D-10). Advanced versions of the conventional four-stroke spark ignition engine are compared with alternative

powerplants, including the two-stroke spark ignition engine, the low-heat-rejection diesel, the Stirling engine, and the gas turbine. The diesel would appear to be the least attractive candidate for a passenger car powerplant because of its low potential for achieving future emissions standards for both NO_x and particulates. The effect of higher cylinder operating temperatures in the low-heat-rejection diesel on NO_x and particulates has not been clearly identified, as yet. It is not entirely clear at this point whether any Stirling engine would have any more potential than the spark ignition engine in meeting more stringent emissions standards. However, the Stirling engine does have several characteristics that enhance its ability to control emissions. The fact that the Stirling engine uses an external-continuous combustion system simplifies the introduction of emission controls because the combustion system is isolated from its closed working cycle. Since the Stirling engine has multifuel capability, it would be amenable to the use of alternative fuels. The use of a less volatile fuel such as No. 2 diesel would have the advantage of minimizing evaporative losses from the fuel system. Finally, the addition of a catalytic reactor to the Stirling engine could further reduce hydrocarbon and carbon monoxide emissions. However, temperatures at the tailpipe of the Stirling engine may not be high enough to provide efficient combustion. Therefore, it may be necessary to position the reactor between the combustion chamber and the preheater. The use of a heated catalytic reactor as previously discussed could have potential for the Stirling engine as well as the spark ignition engine. If it were possible to operate the Stirling engine's external combustion chamber at near stoichiometric conditions to minimize the oxygen content of the exhaust, the use of a NO_x -reducing catalyst might also be explored. Operation of the combustion chamber at near stoichiometric conditions presumes the availability of adequate high-temperature materials, or cooling technology, or both to ensure the suitable durability and life of all high-temperature components.

Both the emissions and fuel economy results for the Mod I and Mod II ASEs are very limited. To date, these results are both incomplete and inconclusive. The urban fuel economy gains continue to be elusive and the fuel economy gains as determined by standard EPA urban/highway fuel economy tests continue to fall short of

prediction. While it appears that the CO and HC emissions can be met by the Mod II ASE, the data for NO_x is marginal at best. Further, both the Mod I ASE and Mod II ASE display a wide range of individual emissions, which suggest uncertainty. And finally, emissions from the Mod II ASE display results significantly different from the Mod I ASE, which suggest uncertainty about the understanding of external combustion systems designed for the ASE's.

These uncertainties, and the general performance of the ASE, suggest that there are considerable reservations that a demonstration of ASE vehicles today would lead to vehicles with any long term emission advantage over internal combustion engines.

REFERENCES

- D-1. Rice, Christian and Casey, Martha: Environmental News. United States Environmental Protection Agency. July 27, 1989.
- D-2. Gallagher, J., Livo, K.B., Hollman, T., and Miron, W.L.: The Colorado Oxygenated Fuels Program. SAE Technical Paper No. 900063, 1990.
- D-3. Lorang, Philip A.: Emissions from Gasoline-Fueled and Methanol Vehicles. Presented at Conference on Methanol as an Alternative Fuel Choice: An Assessment, International Energy Program, Johns Hopkins Foreign Policy Institute, Washington D.C., December 4-5, 1989.
- D-4. State of California Air Resources Board: Low-Emission Vehicles/Clean Fuels and New Gasoline Specifications-Progress Report. December 1989.
- D-5. Pounds, Edward P. III: Fuel Economy: Impacts of the CAFE Standard. SAE Technical Paper No. 900844. 1990.
- D-6. Environmental Protection Agency. 1989 Test Car List - Passenger Cars.
- D-7. Private Correspondence, J. Gallagher, Colorado Department of Health, State of Colorado to R. Shaltens, NASA Lewis Research Center. Exhaust Emissions and Fuel Economy Tests Conducted on Mod-I Stirling Powered Pickup Truck. November 27, 1989.
- D-8. Hare, Charles T. and Gutsell, A. Gregory: Characterization of Mod-I Multifuel Stirling Demonstration Vehicle Emissions. SAE Technical Paper No. 890150. Presented at SAE International Congress and Exposition, Detroit, Michigan, February 27 - March 3, 1989.

- D-9. Haverdink, W.H., Heffner, F.E. and Amann, C.A.: Assessment of an Experimental Stirling Engine-Powered Automobile. GM Research Publication GMR-4817. August 31, 1984.
- D-10. Amann, Charles A.: The Automotive Engine - A Future Perspective. SAE Technical Paper No. 891666. Presented at Future Transportation Technology Conference and Exposition. Vancouver, B.C., Canada, August 7-10, 1989.

APPENDIX E

AUTOMOTIVE STIRLING ENGINE MATERIALS

The high-temperature heater head of the automotive Stirling engine (ASE) represents a severe materials challenge in terms of strength, hydrogen compatibility and permeability, oxidation resistance, and cost. As initially conceived during the late 1970's and early 1980's, the Stirling engine was to be an alternative to the internal combustion engine for automotive applications. This implied a potential production volume of up to 300,000 units per year. Prototype engines at that time used cobalt alloys as the materials for the heater head tubes, the cylinder head, and the regenerator housings. Because of the limited cobalt available in the United States, it was apparent that low-cost substitute alloys would have to be identified, characterized, and validated in actual engine tests in order to be able to mass produce competitive Stirling engines. Research programs were undertaken at NASA Lewis, Mechanical Technology Inc., and United Stirling of Sweden. In a seven-year effort, substitute alloys for the heater head of the Stirling engine were validated in rig and engine tests and shown to be equal or superior in performance to the cobalt alloys initially used in prototype engines.

The substitute alloys are all iron based, thus providing a cost advantage. The present Mod II ASE design contains approximately 25 pounds of cast material for cylinder (piston) heads and approximately 6 pounds of tubing material. The Stirling engine alloys' costs are compared in the following table:

TABLE IX - COST OF STIRLING ENGINE ALLOYS
[Based on cost of raw materials. Cobalt costs \$7.25/lb.]

	Estimated cost, \$/lb
Tubing alloys	
CG-27	2.20
IN-625	3.50
N-155	4.00
Cylinder head alloys	
XF-818	1.75
NASAUT 4G-A1	.61
HS-31	5.55

The proposed substitute cast tubing material, CG-27, costs essentially the same as standard stainless steels, about \$2.00 per pound, and one-half as much as N-155, the cobalt-base prototype tubing material. The proposed substitute cast cylinder head material, NASAUT 4G-A1, costs \$0.61 per pound versus \$5.55 per pound for the cobalt-base prototype cylinder head material, HS-31. The cost of these substitute materials is expected to decrease as demand increases after a market is created.

The materials requirements for some Stirling engine components are similar to those for certain spark ignition engine components; the requirements for other components are very different. For example, the heater head materials are subjected to a severe operating environment and must contain high-pressure hydrogen in the working cycle. The mean pressure of the closed-cycle system varies between 4 and 15 MPa, and cyclic pressures may reach as high as 19 MPa. The heater head tubes operate at a nominal temperature of 820 °C; and the cylinder heads, at 775 °C. CG-27 was selected as the primary alloy for the heater tubes over other candidate materials for its creep rupture properties, oxidation resistance, low hydrogen permeability, and low cost relative to cobalt-containing superalloys.

Alloy CG-27 obtains its excellent oxidation resistance and low hydrogen permeability from the oxides of aluminum and titanium that form on both the inside and outside surfaces of the heater tubes during initial engine operation. These oxides do not reduce in the high-pressure, high-temperature hydrogen; and enough oxygen, a trace contaminant, is present to form the oxides. The trace oxygen level is achieved by doping; that is, by adding small amounts of gases such as CO₂ and CO (0.02 to 1.0 vol %) to the working-cycle gas.

The strength properties of the candidate heater head materials exceed the current design requirements of the Stirling engine: a rupture life of 3,500 hours at a temperature of 860 °C and a stress of 28 MPa. Creep rupture tests on CG-27 in air and high-pressure (15 MPa) hydrogen showed that at the design maximum heater tube temperature, CG-27 has 3,500-hour rupture stresses of 45 and 63 MPa in air and hydrogen, respectively.

Fatigue has been identified as the major failure mode in the cylinder head manifolds of engines. Growth of fatigue cracks and subsequent hydrogen leakage may lead to cylinder housing failures. The fatigue design criteria for the cylinder and regenerator housing require a safety factor of 2 in the stress range produced by the number of pressure cycles in 3,500 hours.

Therefore, it is feasible for the design fatigue stress amplitude to approach a maximum of 240 MPa at 775 °C. Presently, neither the HS-31 nor the XF-818 alloy meets the design criteria in either air or 15-MPa hydrogen. The alloy 4G-A1, with 2.5 times the resistance to fatigue strain of XF-818 and 1.3 times that of HS-31 at 800 °C, is more than adequate. Fatigue tests show that the approximate fatigue-limit stress amplitude for alloy 4G-A1 is 269 MPa. Although it had been identified that the creep-rupture life of the cast components is not their limiting design criterion, an assessment of their rupture life was necessary. Creep-rupture tests in air and high-pressure hydrogen on the cast and braze-cycled 4G-A1 alloy showed that the 775 °C, 3,500-hour, 119-MPa rupture life design criteria for the cast components are satisfied. The 4G-A1 alloy exhibited a 3,500-hour stress rupture strength in excess of 180 MPa at 775 °C.

Cost is always an important issue but, in the case of the ASE, cost becomes even more important because the ultimate objective is to design an engine that could become marketable and price competitive in the automotive industry. Therefore, all of the material selections were strongly weighted toward cost effectiveness. This has contributed to the cost of an automotive Stirling engine being projected to be competitive with the cost of comparable Otto and diesel engines based on an annual production volume of 300,000. Note, however, that in low-volume production and without supporting production needs for other uses, material costs could still be prohibitive.

On the basis of the materials research program in support of the automotive Stirling engine it was concluded that manufacture of the engine is feasible from low-cost, iron-base alloys rather than the cobalt alloys used in prototype engines.

APPENDIX F

STIRLING ENGINES - KINEMATIC AND FREE-PISTON

A TECHNICAL DISCUSSION

INTRODUCTION

Although there are many similarities between the "kinematic" and the "free-piston" Stirling engine (FPSE), the significant differences become major discriminators when selecting an engine for a specific application. A generalized comparison between a kinematic and a free-piston Stirling engine is presented below. A more detailed discussion appears in the sections following the comparison.

The kinematic Stirling engine requires a starter motor similar to an internal combustion production automotive engine. The power output is a function of the torque and speed of a rotating shaft. The engine requires an active power output control system (either a mean pressure system or variable stroke system). The mean pressure control system includes a storage bottle, a compressor and a pressure control valve. Power output is dependent on the engine speed as well as engine pressure. The required power output can be obtained at various engine speeds and pressures. In a kinematic Stirling engine, the oil lubrication system may require maintenance. If oil system maintenance is required, it will be at long intervals since the oil is never contaminated by the combustion process. Also, a dynamic seal is required. The seal is either a sliding seal taking the full engine charge pressure, as in the case of the mean pressure control, used for the MTI Mod II ASE, or a sliding seal taking the oscillatory pressure along with an additional rotary shaft seal as in the variable stroke STM engines.

The free-piston Stirling engine has no active power output control system since power output is determined by the applied load. With a constant mean pressure, the power output is a function of the piston stroke which responds to the load. A specific load therefore results in the piston stroke required to match the output power to the load. A FPSE incorporating a linear alternator, and using helium working gas can be hermetically sealed and does not require a working gas makeup system. The engine operates without an oil lubrication system that could require maintenance. Also, the engine has no starter motor. The FPSE can be started by applying an electric

excitation to the linear alternator. When the excitation is at the resonant frequency of the engine, the piston and displacer will begin to oscillate. This method of start up requires only a minor addition to the system controller logic.

The following discussion gives some general background information about heat engines and Stirling engines specifically. The operation of the Stirling cycle is described along with the hardware used when operating an engine.

DESCRIPTION OF STIRLING CYCLE

Stirling engines are a subset of a more general category of engines known as heat engines. The common trait that links these engines is their ability to convert thermal energy (heat) into mechanical power. The heat can be supplied from any heat source at an appropriate temperature. Each cycle operates on the potential energy that exists between a high-temperature heat source and some low-temperature heat sink. The engine will absorb heat from the heat source and convert some of the heat to mechanical energy; the remaining heat is rejected to the sink as waste heat.

The category of heat engines includes, in addition to the Stirling cycle, the Brayton cycle as used in a gas turbine engine and the Rankine cycle as used in a steam engine. A fourth cycle, (which exists only on paper), is the Carnot cycle. The Carnot cycle represents an ideal cycle with the highest possible theoretical efficiency that can be obtained. Often the efficiency of an engine is expressed in terms of what percentage of the Carnot efficiency it has been able to obtain. Of the heat engine cycles, the Stirling cycle can obtain the highest percentage of Carnot efficiency.

The Stirling cycle is a closed cycle in which a gas known as the working fluid is shuttled back and forth between a hot region of the engine and a cold region. The hot region is called the expansion space and the cold region is known as the compression space. These regions are connected through a system of heat exchangers known as the heater, the regenerator, and the cooler. Because the cycle is closed, the

working fluid is reused as subsequent cycles continue. New working fluid is not brought into the cycle nor is any fluid exhausted during each cycle. Although early engines and some modern day engines use air as the working fluid, the more common working fluid is helium or hydrogen. The high heat transfer rate of helium and hydrogen allows high-speed engine operation, and their low viscosity reduces the losses incurred in pumping the fluid through the heat exchangers.

Stirling cycle engines use pistons moving in cylinders, unlike the Brayton gas turbine engine, which uses spinning turbine wheels. As a general description of the operation, the working fluid is shuttled back and forth between the hot region and the cold region of the engine. This creates a variation in the pressure of the working fluid. When the working fluid is heated, the pressure rises and pushes against the pistons. The force causes the pistons to move, increasing the volume occupied by the working fluid. During this expansion the working fluid does work on the piston. Similarly, when the fluid is cooled, the pressure is lowered and the pistons move inward, decreasing the volume and compressing the working fluid.

Two common arrangements used in Stirling engines are the alpha and the beta configurations shown in figure 19. Although the alpha and beta configurations appear different, they execute the identical thermodynamic cycle. Because the beta arrangement lends itself more easily to a description of the operation, it is described first.

There are two distinct pistons (displacer and power) in the beta engine with two distinct functions. The displacer piston shuttles the working fluid between the expansion (hot) space and the compression (cold) space, alternately heating and cooling it. The power (or working) piston motion is timed (phased) to the displacer piston motion to expand the volume when the working fluid is hot, extracting work from the cycle, and to compress the volume when the working fluid is cold. The difference between the expansion work and the compression work is the net work output of the cycle. A further description of the cycle is contained in the reference

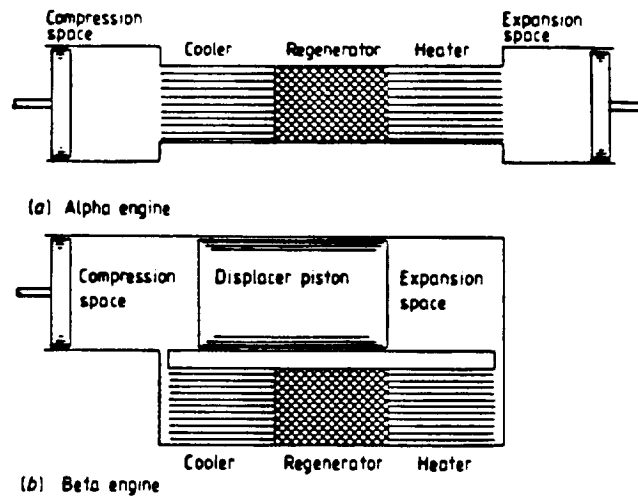


Figure 14. - Common arrangements of Stirling engines: (a) alpha, (b) beta.

F-1, An Alternative Power Plant, The Stirling Engine. The same volume amplitudes and phasing can be obtained in either the alpha or beta configuration. Each engine can generate the identical thermodynamic cycle.

There are many possible ways to configure the cylinders and heat exchangers of a Stirling engine. There are also various ways to cause the desired motions of the pistons and to extract power in Stirling engines. The two broad categories are kinematic Stirling engines and free-piston Stirling engines (FPSE). Kinematic engines use mechanical devices such as cranks or swashplates to control piston motions and to convert reciprocating motion from a piston or pistons to rotary motion to power a device such as a generator, a pump, or a vehicle. Free-piston Stirling engines incorporate an output device, such as an electric generator, a hydraulic pump, or a compressor, directly into the engine. They thus convert reciprocating piston motion directly to useful output power. The FPSE pistons are generally operated as resonant systems employing gas springs, although some "free-piston" engines control displacer motion with linear electric motors or mechanical drives.

Kinematic engines and free-piston engines have some features that are similar and other features that are different. These similarities and differences are addressed in a following section.

COMMON FEATURES

Whether the pistons in the engine move through the use of a kinematic linkage or resonate on gas springs, and whether the engine layout is the alpha or beta configuration, modern Stirling engines have many common features. In all these engines, heat is input to the cycle through the heater. Some of the heat is converted to work and the remaining heat is rejected as waste heat through the cooler. Typically, the heaters and coolers are tubular heat exchangers.

Located between the heater and the cooler is another heat exchanger known as the regenerator. The regenerator serves as a thermal dam, preventing a large percentage of the heat invested in the hot working fluid from being transported directly to the cooler and lost to the cycle. As the working fluid is being shuttled from the hot region of the engine to the cold region, it must pass through the heater and the cooler. If there were no regenerator, the cooler would reject sufficient waste heat to lower the working fluid temperature from the expansion space (hot) temperature to the compression space (cold) temperature. With the regenerator placed between the heater and the cooler, much of the heat that must be removed from the working fluid is transferred to and saved in the regenerator matrix. Nearly all of the heat that must be removed from the fluid is stored in the regenerator; the remaining heat is rejected to the cooling system.

Similarly, when the fluid is being shuttled from the relatively cool compression space to the expansion space, the heat stored in the regenerator is transferred back to the working fluid. The heat supplied to the working fluid from the regenerator is once again much greater than the heat supplied to the fluid via the heater tubes. The regenerator thus acts not only as a thermal dam but also as a thermal storage device

that alternately absorbs heat from the working fluid and then returns it to the working fluid.

Although this principle appears at first glance to be a little obscure, it is the same phenomenon that occurs when a person breathes through a scarf on a cold winter day. Heat is first invested in the scarf when the person exhales. The warm air transfers heat to the material of the scarf, where it is stored. This stored heat is then transferred to the incoming air when the person later inhales. The net result is that the incoming air is preheated with heat from the previously exhaled air. A highly effective regenerator will transfer a large fraction of the heat required to either preheat or precool the fluid as it passes from one temperature region to another. In modern Stirling engines this device is typically a very fine, highly porous metal matrix.

Performance and operating differences exist between a kinematic and a free-piston implementation of the Stirling cycle. The various characteristics of typical kinematic and free-piston engines are described in the following sections. Since this is a comparison of typical engines, some of the statements are generally correct yet not strictly so.

FEATURES OF KINEMATIC ENGINES

The kinematic Stirling engine is characterized by the use of a mechanical linkage or a system of linkages to coordinate the movement of the pistons and to transfer power generated to the load. This is typical of the Stirling engines designed for the automotive application and early generator sets. All Stirling engines made before the late 1960's were of the kinematic configuration.

The power output of the kinematic engine is in the form of a rotating shaft. The power level is typically modulated through the use of a mean-pressure control system or a variable-stroke control system, such as a variable-angle swashplate. With either of these systems the user will notice a change in the power output in a manner

similar to common internal combustion engines. The power output will be a function of the engine speed for any given throttle setting, with various throttle settings available. A change in the throttle setting will cause the engine to follow a new curve of power output versus speed.

When a mean-pressure control system is used, as in the Mod I and Mod II ASE's, a compressor, a control valve, and a storage bottle are used to vary the inventory of the working fluid in the cycle. As the mean pressure of the working fluid is increased, more molecules of gas are heated and cooled during each cycle and subsequently more heat is converted to work. When at high mean pressure the engine produces a high-pressure swing within the cycle. As less power output is required, the mean pressure of the working fluid is lowered and less heat is converted to work. A smaller pressure swing now exists. The majority of kinematic engines built to date have been of the mean-pressure control type.

When a variable-stroke control system is used, as in the STM engine, the working fluid inventory, and therefore the mean pressure of the cycle, remains fixed. The stroke of the pistons is changed. As more power output is desired, the piston stroke is increased, causing a large volume variation and a larger pressure swing. The amount of heat converted to work increases. As less power output is desired, the stroke is shortened, causing a relatively small volume variation and a smaller pressure swing. Little heat is now converted to work.

Kinematic engines use a dynamic seal to isolate the working fluid from the crankcase and also to prevent the oil used in the crankcase from migrating into the working space. Oil leakage into the working fluid can potentially foul heat exchangers and through decomposition add other gases to the working fluid, which would affect performance. However, experience in the NASA ASE project has shown that the first effect to be noticed is a fouling of the piston rings, which causes rough operation (vibrations) of the engine. The variable-stroke engine normally pressurizes the crankcase to the mean-pressure level of the working space and therefore requires an

additional seal in the system. One seal must isolate the pressure swing in the working space from the mean pressure of the crankcase and also prevent oil migration into the working space. This seal has the high-level, time-varying working space pressure on one side and the mean pressure with oil lubrication on the other. The engine needs one seal of this type for each cylinder of the engine. The second seal is a rotary seal at the output shaft of the engine that must prevent the mean-pressure level of the crankcase from escaping to the outside atmosphere. This rotary seal has the oil-lubricated mean engine pressure on one side and the outside atmosphere on the other. Only one seal of this type is needed for each variable-stroke engine.

In the mean-pressure control engine a sliding seal must prevent the pressure level of the working space from escaping to the crankcase, which is at atmospheric pressure. This same seal must also prevent the oil from migrating into the working space. This seal operates with the high-level, time-varying working space pressure on one side and the outside atmosphere with lubrication oil on the other side. One seal of this type is needed for each cylinder of the engine.

Kinematic Stirling engines commonly utilize hydrogen or helium as the working fluid. Hydrogen-filled engines typically can be smaller than helium-filled engines for the same power level. However, some hydrogen will permeate through the high-temperature heater tubes (helium will not), resulting in a higher working fluid makeup requirement. Air or nitrogen can be used as the working fluid but result in substantially larger engines.

Mean-pressure-control kinematic engines typically have a crankshaft and flywheel system similar to that in a common internal combustion engine. During the expansion phase of the cycle, power is transmitted to the kinematic linkage from the thermodynamic cycle. Some of this power is stored in the inertia of the linkage and the flywheel. At another phase of the cycle some of this inertial energy stored in the kinematics is returned to the cycle as the work of compressing the working fluid. The

efficiency of this storage system is very high and remains so over a wide range of speed.

FEATURES OF FREE-PISTON ENGINE

The FPSE is generally characterized by the lack of any linkage or kinematic system for either the transfer of power to the load or the timing of the piston motions. However some "free-piston" engines do provide displacer motion control with a linear electric motor or mechanical drive device. The engine is normally a resonant device with no oil system, piston stroke control system, or pressure control system. All FPSE's to date have been of the piston beta configuration with a power piston and a displacer. Such engines are currently being developed for use in space power applications, where long life and low specific mass are the major design drivers. Programs are under way to develop the FPSE for other terrestrial applications. These include generator sets, gas-fired heat pumps, and solar-dish electric power for utility service.

The FPSE is a resonant device that operates on the Stirling cycle. The power piston and the displacer resonate as the engine operates. The motions are governed by the masses of the piston and the displacer, along with the spring forces and damping that exist in the engine. Spring forces are supplied through the volume variation of the gas springs and the working space. The damping on the displacer is primarily due to the losses in the engine; the damping on the piston is primarily due to the load. The motions of the piston and the displacer follow the dynamic theory of spring mass systems with damping applied. Both the size of the spring and the damping coefficients are designed such that the motions cause the desired Stirling cycle to occur.

The FPSE power output is in the form of linear motion and therefore lends itself to three basic forms of power conversion: The power piston can drive a linear alternator that converts the engine power output to electricity; it can drive a linear

pump that displaces a fluid; or it can drive a compressor that compresses a gas. Each of the loads has unique characteristics that can alter the engine operation. A linear alternator is very similar to a pure damper, but a compressor has some amount of spring content. A fluid pump is a form of Coulomb load, similar to pure friction. These spring and damping factors become part of the total spring, mass, and damping system that determines the motions of the piston and the displacer.

The mean pressure of an FPSE remains fixed during operation. The load conversion device is located in the pressure vessel of the engine. The engine can be designed so that there are no penetrations into the pressurized engine housing that require dynamic seals. The engine can therefore be hermetically sealed for long-life applications. With the mean pressure being maintained at some constant value, the power output is typically regulated through the load.

As the load against which the engine performs work is varied, the engine will respond by varying the stroke of the piston and the displacer, with the mean pressure and the frequency of the engine remaining fixed. The change in the load appears to the engine to be a change in the damping applied to the power piston. Through the dynamics that determine the spring mass system resonance, the change in piston damping alters the piston stroke, the displacer stroke, and the displacer motion relative to the power piston motion, yet has a negligible effect on the system resonant frequency. In a manner similar to the variable-stroke kinematic engine, the change in stroke of the FPSE alters the power output by changing the volume variation within the engine.

APPENDIX G

INDUSTRY RESPONSES



March 13, 1990

Dr. J. Stuart Fordyce
Director of Aerospace Technology
National Aeronautics & Space
Administration
Lewis Research Center
Cleveland, OH 44135

Dear Dr. Fordyce:

The following comments are a result of our meeting with Messrs. Beremand and Shaltens during their January 31 visit to review the recently completed Department of Energy (DOE) automotive Stirling engine program. As you know, Cummins Engine Company is currently pursuing the free-piston Stirling engine technology for solar electric conversion systems, so your review of the DOE funded kinematic Stirling engine is of interest.

The Stirling engine has a number of characteristics which make it an attractive alternative when compared to current diesel engines. Along with the known high efficiency are its capabilities for multi-fuel operation (which consists of a broad range of liquid and gaseous fuels) and its unique capability to use alternate heat sources such as solar energy. In addition, emissions from the Stirling engine are generally believed to meet today's standards for use in a light-duty truck application. The Stirling engine's total number of parts, as well as fewer moving parts, suggest that the potential exists for lower maintenance requirements and longer life/service intervals. Also, because the oil used for lubrication in the Stirling engine does not see the combustion products, oil and filter changes should be reduced significantly. Finally, the free-piston Stirling engine may have even longer life because it has even fewer moving parts than the kinematic type Stirling engine, and because oil is not required for lubrication, oil seals are not required.

Although the Stirling engine has a number of advantages, we believe the Stirling technology is in its infancy and requires substantial development prior to its introduction into a major marketplace such as for the automotive application even if the market becomes reality. Major unknowns are the manufacturing requirements and the total costs for an engine with radically

different components, such as the high temperature heat exchangers and regenerators, when compared with technology used in current engines. The life capacity and mature cost of materials required in the high temperature environment of the Stirling also remain unknown. Other areas of risk include development of advanced high temperature lubricants (for dry bearings) and cost effective magnetic materials for linear alternators, currently proposed for the free-piston Stirling conversion systems. The complex heat transfer and fluid flow phenomenon inside the Stirling engine is still not well understood and requires additional work. In addition, larger capacity radiators for cooling the Stirling engine are required for all applications and the size may be impractical for today's automotive application.

With the existence of two fully developed commercial engines (diesel and spark ignition) in place, we believe that the high production volume required for the automotive market will be very difficult (if not impossible) to penetrate for any new engine. Introductory markets should focus on specialty applications which utilize the advantages of the Stirling engine, have initial low production requirements, have little or no competition and price sensitivity is not an issue. Engine size should be below 25 kW (33 hp) power levels until the manufacturing issues can be fully understood along with unit cost. At Cummins the successful demonstration of proof-of-design engines must be completed before entering into the manufacturing prototype stage. After demonstration of the technical goals, sufficient reliability and durability data along with in-service evaluations (or demonstration) must be obtained from prototype engines (at least 50 to 200 units) before a decision on engine production could be made. After starting the prototype phase, it would take from 5 to 7 years before mature market production could be achieved.

Introductory markets would include applications for power generation systems (such as solar electric Stirling systems) for remote areas, replacement power sources for areas such as California, specialty military niches, irrigation pumping systems, generator sets for pleasure boats, and other renewable energy conversion systems.

We believe that there should be an on-going cooperative effort between government and the U.S. industry in high risk development efforts such as the Stirling engine. Currently Cummins Engine Company is spending the majority of its development and research funds to meet the current (and future) EPA and California (CARB) regulated emission standards for our

March 13, 1990

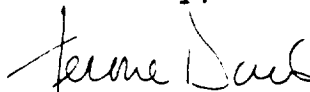
primary product, diesel engines. Few resources are left for the development and evaluation of future products, primarily because of the limited resources available for high risk technologies such as free-piston Stirling engines. Today there appears to be little government interest or financial support and no incentives exist for the private sector to engage in pursuing the high risk technologies which may be of benefit for the nation environmentally and to help create jobs in the U.S. job market.

In conclusion, it appears that a broad knowledge base has been provided under the DOE automotive Stirling engine program, however, the data provided shows that the kinematic engine has not met all of its technical goals. Based on this data, we do not believe that the next step is a government/industry cost-shared fleet demonstration program. However, we do believe that an on-going industry/government program is needed to reduce risk and to foster commercialization of high risk technologies such as the free-piston Stirling engine.

I hope this information is helpful to you for your report to the U.S. Congress.

If I can be of any further assistance, please get in touch.

Sincerely,



President

J.Davis/sb

Telephone: (812) 377-3743

Facsimile: (812) 377-3334



John P. McTague
Vice President
Research

Ford Motor Company
P O. Box 1603
Dearborn, Michigan 48121-1603

February 22, 1990

Dr. J. Stuart Fordyce
Director of Aerospace Technology
National Aeronautics and
Space Administration
Lewis Research Center
Cleveland, OH 44135

Dear Dr. Fordyce:

In accordance with your request, representatives of my staff met with NASA and DOE representatives to receive an update on the status of Stirling engine technology. Unfortunately, due to a prior commitment, I was not able to attend the meeting, but I would like to provide you with our reactions to the presentation and our comments on the Stallings amendment.

As you are aware, Ford Motor Company discontinued development work on the Stirling engine in 1979. We took this step in order to concentrate our resources on technologies critical to the future of the company, including the development of those technologies required to meet fuel economy and emissions regulations. In the powertrain area, we felt that this objective could best be met, within the required time frame, by concentrating our efforts on improving the spark ignition (SI) piston engine.

In the future we are likely to face even more stringent regulatory requirements in the areas of fuel economy and emissions. Thus, the targets that the Stirling engine must meet in the future are even more demanding than those of the past.

Based on the vehicle data presented during the meeting and our own reviews of the Stirling program from time to time, we see some attractive attributes to the Stirling engine, namely its multifuel capability and its relatively noiseless operation. However, it appears to us that several significant open issues need to be resolved before Ford Motor Company would develop any renewed interest in this concept. These issues are as follows:

- There is no evidence that the fuel economy of the Stirling engine will equal or better the best-in-class 1990 SI piston engine technology, measured at equal vehicle performance. Actually, the fuel economy of the Stirling engine would have to be substantially better in order to warrant the investment in a totally new technology.

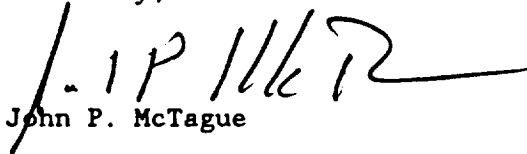
- There is no evidence that the 0.4 gram per mile NOx target can be met with the current Stirling technology. It should also be kept in mind that Tier II requirements in the current legislative proposals would require 0.2 gram per mile NOx by the year 2004. There certainly is no evidence that these goals are achievable with the current Stirling technology.

The NOx control issue is of particular concern. In today's automotive emission control systems, NOx is catalytically reduced in the exhaust stream, and this technology makes it possible to reach the 0.4 grams per mile in many SI engine applications. In the case of the Stirling engine, however, the entire NOx control task must be performed within the burner since catalytic reduction is not possible in an exhaust stream containing excess oxygen. Achievement of the proposed 0.4 gram per mile or 0.2 grams per mile in the long term may well be beyond the capability of continuous combustion technology.

- We also question whether it will be possible to manufacture the Stirling engine in high production volumes at low cost with very high reliability. Our current assessment indicates that little work has been done in this area. Stirling engine manufacturing practices appear to be complex and costly, and certainly this concept would require large new investments in facilities and tooling that would have to be justified by major product benefits.
- We also have concerns about the packageability of Stirling engine systems, i.e. the engine plus cooling system, in the engine compartments of many of our future vehicles.
- Finally, there is the problem of working fluid containment which still appears to be unresolved.

According to our understanding, the Stallings amendment proposes that the next logical step is a government/industry cost-shared commercial demonstration program. Based on the significant open issues raised above, we do not agree with such an approach. Although we do not recommend additional government expenditures for the Stirling engine, if they are made available, they should be targeted at resolving these issues before commercialization is undertaken.

Sincerely,


John P. McTague

March 6, 1990

Mr. Donald G. Beremand
NASA Lewis Research Center
Stirling Technology Branch
21000 Brookpark Road, MS301-2
Cleveland, OH 44135

Subject: GRI's Stirling Engine Program

Dear Mr. Beremand:

This letter is in response to your request to obtain GRI's perspective on the prospects for commercialization of Stirling engines. I would like to share with you GRI's experiences and outlook regarding Stirling engines and to indicate what steps may be needed to improve the chances of commercializing the Stirling engine.

Since 1980 GRI has been supporting the development of stationary natural gas-fired Stirling engines as alternative prime movers to conventional internal combustion (IC) gas engines. The impetus for GRI's Stirling engine R&D program has been the Stirling's potential for lower emissions and less maintenance than conventional engines. To date, GRI has invested over \$25 million in contractual R&D funds to develop a variety of stationary gas-fired kinematic, and free-piston Stirling engines for driving residential and small commercial vapor compression heat pumps and cogeneration systems. While these R&D efforts have advanced the state-of-the-art, attempts at commercializing the engines have been unsuccessful. Based on these experiences, we believe the Stirling engine cannot compete on a first cost basis with reciprocating IC engines, and that barring introduction of mass-produced markets for Stirling's, such as transportation, we believe it is unlikely that the Stirling engine cost can be sufficiently reduced to compete with conventional prime movers. However, we do believe the Stirling engine has unique attributes that no other prime mover can likely attain: very quiet operation, exceptionally low emissions and the potential for long periods between service. While many of the Stirling engine's attributes are intangible, they may in the long term provide the opportunity to achieve commercial success. For this reason, GRI has recently taken the position of maintaining a lower funding level technology base R&D program on Stirling engines to address key technical issues in order to improve their competitive position. As a consequence GRI's Stirling engine efforts are directed to two fronts, 1) an assessment of worldwide Stirling engine developments to determine the most commercially viable designs and level of their development, and 2) a technology base program directed toward finding solutions to technical problems that hinder the commercialization of Stirling engines. These R&D efforts are likely to be continued by GRI in the next few years.

Mr. Donald G. Beremand
March 6, 1990
Page Two

In regard to the commercialization of Stirling engine's for automotive applications it is GRI's belief that only government mandated legislation can create a market for low pollution gas engines such as the Stirling. At present, industry has not been willing to invest their resources in Stirling engines, that not only cost considerably more than state-of-the-art automotive engines, but whose attributes have not been sufficiently demonstrated to reduce the technical risks. For example, technical barriers such as weight penalty, slow start time and seal degradation, need to be overcome before any large investments can be justified. In addition, market barriers such as lack of customer incentives and lack of a service infrastructure have not been addressed.

To create the financial incentives for engine manufacturers to commercialize Stirling engines, it is an important first-step that the federal government pass pollution control legislation requiring further reductions in automotive fleet average emissions. Without such legislation, it is unlikely that the Stirling engine can compete in the marketplace.

I have filled out the attached questionnaire you requested that suggests the type/size of the proposed Stirling engine automotive fleet demonstration program. Assuming "success" of the demonstration, I have listed the timetables and possible financial investments needed to bring the automotive Stirling engine into mature production.

If you require any further information on GRI's Stirling engine program, please feel free to contact me.

Sincerely,



J. M. Clinch, Ph.D.
Senior Project Manager
Commercial Space Conditioning

JMC/jad

QUESTIONS FOR INDUSTRY

1. What advantages do you see for Stirling engine that make it attractive to you as a manufacturer? *Potential for lower pollutant emissions and longer maintenance intervals at a modest cost premium over conventional engines.*
2. What are the disadvantages or shortcomings of Stirling that might discourage you to manufacture Stirling engine? *Uncertainty of market for Stirlings. Insufficient data on life, reliability & failure modes of engines.*
3. What technology barriers do you believe exist for the Stirling? *Slow start time. High temperature heater head problems, seal problems.*
4. What are the market needs for a new type of engine such as Stirling? *Legislation which creates market for low pollution engine.*
5. What market barriers exist for a new type of engine such as Stirling? *Engine cost & weight are major barriers. Also lack of service infrastructure.*
6. What do you see as the initial application(s) and market(s) for the Stirling engine?

Application(s) and Engine size(s)?

Government fleet vehicles eg. Post Office ASE size (40-80 hp)

Initial market sizes and initial engine cost?

10,000/year \$5,000/engine (ASE size)

Initial production run and mature engine cost?

2,000 at \$3,000/engine

How many years before mature market production? Annual production? *10 years after initial market. Annual production depends on pollution control legislation. Legislation will create market and size of market.*

7. Describe a demonstration program that you would require before entering into initial production of a new type of engine such as Stirling?

Number of engines? *250*

Type of testing? *City, Suburban, Fleets, North-South Clinics (50 of each)*

Component and system performance

Endurance or life and reliability

In-service evaluations

} *All*

8. What is your estimate (timetable) to bring a new engine such as Stirling into production?

8 years for the design and development?

6 years to demonstrate performance? endurance? ASE size?

2 years for in-service evaluations? ASE size?

12 years to initial production? 10,000 size? plant cost? \$100 million

16 years to mature production? 500,000 size? plant cost? \$400 million

9. What is governments role in the commercialization of a new engine such as Stirling? Why? *Pass legislation requiring a moving reduction in Fleet average emissions. Support demonstration program with Federal, State & local government agencies.*

10. Considering the advantages attributed to Stirling and the progress made in advancing Stirling technology, why has industry not been interested in pursuing it? *No incentives to pursue Stirling technology. Stirling engines cost more & are heavier than conventional engines so why develop engine like Stirling unless you have to.*



General Motors Research Laboratories
Warren, Michigan 48090-9055

February 6, 1990

Mr. Richard K. Shaltens MS 301-2
NASA Lewis Research Center
21000 Brook Park Road
Cleveland, OH 44135


Dear Dick:

We appreciated the opportunity to comment on the automotive Stirling engine during your visit of January 23, 1990. Our opinions are based on our own experience with the Stirling engine when it was an active project here during the decade of the 1960s, and also on our tests of the Mod I engine installed in the Spirit automobile in 1984, conducted in a cooperative DOE program. These comments are made from the position of a company in the business of producing automobiles and light- and medium-duty trucks.

The automotive Stirling engine can claim some advantages relative to the generic internal combustion engine. It is reasonably quiet, can burn alternative fuels, and has a well shaped torque curve. However, we have also made the automotive gasoline engine reasonably quiet, and it, too, will operate on the leading alternative fuels proposed for highway vehicles, viz., M85, methanol and natural gas. Although there is always room for improvement in the torque-curve shape of the conventional engine, the transmission satisfactorily compensates for its deficiencies.

These attributes of the Stirling engine must be weighed against its shortcomings, as follows:

1. In our view, it is too large, heavy and expensive to be competitive with the spark-ignition engine that dominates the automotive field.
2. In our evaluation, it showed unacceptably poor fuel economy without commensurate compensation in performance capability.
3. Regulators are considering a future NOx standard of 0.2 g/mi. We are not convinced the Stirling engine can satisfy such a difficult standard, since it can derive no help from a reducing catalyst.

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4. We think the consumer would object to the time spent waiting for a cold engine to achieve operating temperature. This problem seems inherent to external combustion engines, a point made obvious to us in our steam engine experience of the late 1960s.
5. We are convinced the consumer would not accept the current hydrogen leakage rate. Time and/or miles between service stops for replenishment of hydrogen needs to be prolonged to match infrequent service stops already accepted with current cars, e.g., changing oil.
6. Although the Stirling Spirit performed well in the wind-tunnel cooling tests we ran in 1984, we are still concerned about the unusual situations, e.g., grade climbing in a desert climate, where the cooling fans would cycle on to control coolant temperature. The reason for this concern is the sizable fraction of available engine power consumed by the normally inoperative cooling fans, which would be reflected as a sudden substantial drop in performance capability.

Because of these points, we foresee no place for the Stirling engine in our present business. This being the situation, we see no point in commenting on a demonstration program. There may, of course, be non-automotive applications where the Stirling engine proves attractive.

We cannot speak with any authority on potential applications outside of our segment of the automotive field. However, possibilities that come to mind include (1) the derivation of power from solar energy, (2) use in remote geographical areas where conventional liquid fuels might have to be replaced by solid fuels like wood, peat, or coal, (3) applications where an engine could advantageously be operated on stored heat, and (4) marine (underwater?) use, where the availability of a large cold heat sink might benefit the Stirling cycle. It seems likely that in any of these applications, the ability of the engine to contain its charge of working fluid for prolonged periods would be essential.

Although in our experience, the Stirling engine has proven to be a poor match to the requirements of the light-duty highway vehicle, this in no way reflects on the competence of your prime contractor, MTI. During our interactions with them, we were impressed with their approach to the project and with the capabilities and diligence of their people. Congress needs to appreciate that when the government elects to pursue high-risk alternative powerplants for the automotive sector, this inherently entails a high risk of failing to meet program objectives. That is the nature of research and is not, in the present case, the fault of MTI.

Page 3
February 6, 1990

We understand that development of the Stirling engine is expected to continue for non-automotive applications. We plan to watch those developments, just as we follow progress on a variety of other powertrain options, in case the evolution of our business alters the engine situation. Meanwhile, if the Mod II engine were available for test in a vehicle, we would seriously consider evaluating it at no charge, just as we did the Mod I in 1984, in order to make certain that we have not missed anything. We would be most interested in a passenger-car installation, with automatic transmission, since that is the heart of our business. In decreasing order of interest are a passenger car with a manual transmission and a truck or van with any type of transmission.

Sincerely,



Charles A. Amann
Research Fellow
Executive Department

CAA:mjb

JOHN DEERE TECHNOLOGIES INTERNATIONAL, INC.

JOHN DEERE ROAD, MOLINE, ILL. NO. S. 61265 6098 U.S.A.

EDWARD S. WRIGHT
President



12 February 1990

Dr. J. Stuart Fordyce
Director of Aerospace Technology
National Aeronautics & Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Dear Dr. Fordyce:

It was a pleasure to renew old acquaintances with Messrs. Beremand and Shaltens on their visit January 30th. At their request, I am responding to your letter of 26 December 1989.

As you know, Deere & Company is one of the world's foremost engine design development and manufacturing organizations. We are well known for the millions of reliable cost-effective engines we have manufactured since 1917 for farm tractors and a variety of other farm and construction equipment, including the production of close to three million diesel engines. In fact, we are the nation's leading producer of off-highway diesels under 300 hp. These engines have consistently led their competition in such innovations as rotary fuel pumps, turbocharging, intercooling and high output.

Perhaps less well known is Deere's innovation in activities involving alternative engines, such as gas turbine engines, rotary engines, and Stirling engines. In the years 1965 through 1972, for example, Deere designed and tested extensively an innovative gas turbine engine for tractor and earthmoving applications which represented a substantial breakthrough in both manufacturing cost and performance. This engine was developed to production status but was not committed to production because it is *extremely* difficult and risky to introduce a completely new type of engine to the commercial marketplace by *any* single company. An extensive evaluation resulted in an executive decision to commit to a diesel engine, which was under simultaneous development for the intended application. This decision was a business decision heavily influenced by the risk of introducing a new type of engine.

Currently, Deere & Company is committed to produce an innovative stratified charge rotary engine. We are the *only* engine company in the world currently committed to produce this engine. The decision to commit to this risky path was possible *only* because of substantial R&D funding by, and production requirements of, the U.S. military.

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JOHN DEERE TECHNOLOGIES INTERNATIONAL, INC.

Dr. J. Stuart Fordyce
12 February 1990
Page Two

It is apparent that Deere is exactly the type of innovator required to commercialize a totally new engine like the Stirling engine. With this prospect in mind, Deere invested considerable resources from 1985 through 1989 in thoroughly investigating Stirling Engine technology and the manufacturing costs and techniques necessary to make it practical.

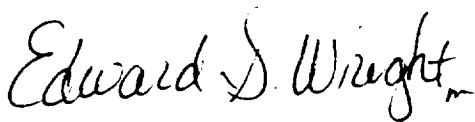
The results of this investigation were presented in testimony to Congress in 1988 and 1989 when we explained in detail what was needed to commercialize the engine. Namely to conduct a commercial based field test in the hands of potential buyers of a statistically significant number of prototype engines. We estimated a cost of \$85 million for this project of which \$20 million (25%) was necessary to be provided by the government.

Unfortunately, that support was not forthcoming. We dropped our project, the skilled, experienced team we assembled was disbanded, and the net result is that neither we, the engine developer, the Department of Energy, the Congress, the potential customers, or the engineering community have the foggiest idea whether the engine should have been commercialized or not.

What is known is that the taxpayer has paid \$130 million for a currently useless technology-- useless not because of any inherent defect, but because the Department of Energy naively believed that the technology had been developed to the point where an engine manufacturer could make rational decisions to commit large scale resources to its commercial deployment.

Since we have already stated our position fully to the Department of Energy, NASA, and the Congress, detailed answers to the attached questionnaire seem superfluous. Nevertheless, we are glad to reply briefly in the spirit of cooperation we have always maintained towards this project.

Sincerely,

A handwritten signature in cursive script that reads "Edward S. Wright".

Edward S. Wright
President
John Deere Technologies International, Inc.
Phone 309/765-5462

mgm
enclosure

1. What advantages do you see for Stirling engine that make it attractive to you as a manufacturer?
It is efficient, cost effective, and capable of operation from any reasonable heat source, including alternative fuels, solar collectors, and waste heat.

2. What are the disadvantages or shortcomings of Stirling that might discourage you to manufacture Stirling engine?
The major known disadvantage is that it is still a laboratory engine and the risks inherent in commercializing it are too high for a profit making company.

3. What technology barriers do you believe exist for the Stirling?
We do not see any technology barriers. Obviously, a great deal of optimizing, value engineering, and reliability growth needs to be accomplished.

4. What are the market needs for a new type of engine such as Stirling?
An initial introductory market which is willing to pay a modest premium for the engine advantages is a necessity. For example, we identified a need in urban light delivery fleets for the ASE.

5. What market barriers exist for a new type of engine such as Stirling?
The market barriers are substantial. Among others, risk of committing to new technology, high initial selling price, revenue lag between initial order and reorder, fact that *no* sales can be realized until product is tested extensively in customer's hands, etc..

6. What do you see as the initial application(s) and market(s) for the Stirling engine?
I have no idea. There was a potential in the alternative fuel urban light delivery fleet market, but that opportunity is past.

7. Describe a demonstration program that you would require before entering into initial production of a new type of engine such as Stirling?
As we extensively explained at the time we were willing to tests its viability, at least forty engines in testing for at least eighteen months in customer's hands would be a minimum possible requirement.

8. What is your estimate (timetable) to bring a new engine such as Stirling into production?

Specifically with regard to the ASE:

10 years for the design and development?
3* years to demonstrate performance? endurance? _____ size?
3* years for in-service evaluations? _____ size?
3* years to initial production? _____ size? plant cost?
6 years to mature production? _____ size? plant cost?
19 Years Total *to be conducted concurrently

9. What is government's role in the commercialization of a new engine such as Stirling? Why?

Based on our experience, where the government refused to fund the logical last stage of Stirling engine development while continuing to fund impractical, unproven gas turbine developments, the government's role in this type of commercialization needs to be strongly reassessed.

10. Considering the advantages attributed to Stirling and the progress made in advancing Stirling technology, why has industry not been interested in pursuing it?

On the contrary, industry has been interested in pursuing the Stirling Engine. It was the government's failure to continue to risk-share in a highly risky venture which sunk the ASE program.

Kennedy Engine Company, Inc.

PHONE (601) 392-2200 FAX 601-392-9507

MOTSIE ROAD AT J-10 (CEDAR LAKE EXIT) RT. 6
BILOXI, MISSISSIPPI 39532

1. Advantages of the Stirling engine that make it attractive to Kennedy Engine Company as a manufacturer would include the growing need to solve air pollution problems and to reduce the nation's reliance on fossil fuels. The future demands will only increase as the nation struggles to meet clean air and water standards thus insuring a future market for the production of the Stirling engine.

2. Disadvantages or obstacles to overcome in initiating the manufacture of the Stirling engine would all bear on the fact that there is no manufacturing infrastructure in place for this new technology. Because establishment of that infrastructure would require a large capital investment and because the venture would be viewed as high risk by possible investors, loan and seed funding will be difficult to obtain. There is at present only a limited ready market for the Stirling engine.

3. It is not possible for Kennedy Engine Company to predict what technology barriers exist for the Stirling engine because Kennedy Engine Company has not had an opportunity to evaluate the engine by way of hands-on testing. Future government programing of Stirling engine commercialization should include making the engine available for testing by prospective manufacturers.

4. Infrastructure and training would be needed to market a new engine such as the Stirling. Existing engine business infrastructure could be adapted to the special requirements of the Stirling technology.

5. The lack of an established network for service, training, and spare parts would present initial market barriers for the Stirling engine. Also, the established engine manufacturers are not likely to welcome the entrance of a new engine competitor in the marketplace.

6. Kennedy Engine Company currently has standing orders for Stirling engines. The engine application would be in stationary generator sets in the 50KW to 200KW range. The initial market size would be between 2,500 and 3,000 generator sets at a cost of \$50,000.00 to \$60,000.00 per unit.

7. Kennedy Engine Company would require a demonstration program that would allow it to evaluate concepts/prototypes with hands-on demonstrations with Stirling engines in several modes of operation and in multi-fuel conditions. We would like to demonstrate life of engine and reliability factors. Prospective customers would require field test engines for their own

evaluation. In order to promote the commercialization of the Stirling technology, we believe that the government should conduct a similar program.

8. We estimate the following timetable to bring a new engine such as the Stirling into production:

- 5 years for design and development
- 3-5 years to demonstrate performance
- 1-2 years to demonstrate endurance
- 10 years for in-service evaluations
- 3-5 years to initial production
- Plant cost- \$50,000,000.00
- 8 years to mature production

9. We believe that the government has the responsibility to help achieve the goal of clean air in this country and to assume some of the risk and cost in establishing a new manufacturing infrastructure to further this objective. The market can then dictate the need.

10. Industry has had little incentive to pursue the Stirling engine technology since the clean air standards have been formulating slowly and enforcement still remains questionable. The establishment of infrastructure is so capital intensive and risky so as to deter most businesses from venturing into it.

APPENDIX H

AGENCY RESPONSES



DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AIR FORCE SYSTEMS COMMAND
ANDREWS AIR FORCE BASE DC 20334-5000

REF ID: A66774
ATTN OF LGT

JAN 8 1990

SUBJECT Stirling Engine Technology for Use by the Automotive Industry

TO Mr Richard K. Shaltens
NASA Lewis Research Center
Stirling Engine Project Office/
MS301-2
2100 Brook Park Road
Cleveland OH 44135

1. The Air Force Management and Equipment Evaluation Program (MEEP) was invited by the National Aeronautics and Space Administration (NASA) to participate in the testing and evaluation of the Stirling technology in November 1985. Purpose of the testing/evaluation was to assess the feasibility of using the Stirling technology for use in the automotive industry.

2. Testing/evaluation of the Mod I version of the Stirling engine was conducted while installed in a multipurpose van and a D150 pick-up truck by our four field MEEP activities. Summary of the results and our position on the commercialization of the Stirling technology is as follows:

a. The potential of reducing maintenance cost benefits versus the conventional gasoline engine:

- (1) One ignition plug in lieu of four, six, or eight spark plugs.
- (2) No ignition points, stator, rotor, distributor cap or ignition wiring.
- (3) No catalytic converter.
- (4) No muffler.
- (5) No oil or filter changes.
- (6) No engine tune ups.
- (7) Fewer moving parts to wear or cause friction.
- (8) Higher operating efficiency.

b. Other benefits

- (1) Lower noise level

JAN 12 1990

- (2) Somewhat increased fuel economy during open highway operation.
- (3) Reduced emissions.
- (4) Operates on multifuel, i.e., leaded/unleaded gas, diesel, and JP-4 aircraft fuel.

c. Shortfalls/disadvantages versus the conventional gasoline engine.

- (1) Experienced difficulty during cold weather use in getting the Stirling engine to start. This was usually associated with the fuel control system.
- (2) Excessive hydrogen (H₂) leakage during first part of the evaluation. However, the problem improved as the contractor technicians gained more experience.
- (3) Numerous failures in the electronic external control systems.

During the evaluation period, it was necessary to have contractor technicians go to the test/evaluation site to troubleshoot, repair or replace failed component parts/systems. This was necessitated by the new technology. There is no infrastructure developed that would allow you to go to a local repair shop or manufacturer/dealer to get malfunctions corrected. In addition, our repair service technicians are not yet trained in the Stirling technology or mechanical components.

d. Recommended demonstration fleet.

(1) We do not recommend further demonstration/evaluation unless there are stated interests from a manufacturer to develop a prototype fleet equipped with the Stirling technology automotive engine.

(2) If this develops, the Air Force MEEP would be willing to evaluate a demonstration fleet of up to 50 vehicles.

e. Stirling demonstration results

(1) The evaluation/demonstration results of the Stirling technology were positive. It was demonstrated through our field evaluation that the Stirling technology can be adopted for use by the automotive industry. However, we are not in the position to evaluate or assess whether this would or could be cost effective.

f. Long term sponsor contributions.

(1) Charter of the Air Force MEEP is to test and evaluate products that have already been developed and are on the market, at no cost to the Air Force. We cannot provide or commit funding of the Stirling technology. We operate under the 'Try Before You Buy' concept prior to recommending adoption for Air Force use.

(2) The MEEP will participate in further testing/evaluation of the Stirling technology if and when asked/invited to do so. However, we do recommend that there be some involvement by an interested manufacturer prior to further testing/evaluation of this technology.

3. We hope that this information will be sufficient for your use in putting together a draft report on the commercialization assessment of the Stirling technology. In addition, we appreciate the opportunity of working with all of the agencies involved in this endeavor. If we can be of further assistance, my point of contact is Mr Ezra Lane, (301) 981-3206.



FRED R. HESTER
Director of Transportation
Deputy for Logistics

cc: HQ USAF/LETN
NASA Wash DC (Mr Ault)



10 FEB 1 1990

Department of Energy

Washington, DC 20585

January 17, 1990

Mr. Leonard A. Ault
Acting Director
Technology Utilization Division
NASA Headquarters (CU)
Washington, DC 20546

Dear Mr. Ault:

During our recent meeting at NASA Headquarters, in connection with the Stirling commercialization bill HR 1759, we discussed the DOE experience with the demonstration of electric and hybrid vehicles. I have written below some background information about the demonstration and some comments on lessons learned.

On September 17, 1976, the U.S. Congress passed the Electric and Hybrid Vehicle Research, Development and Demonstration Act (Public Law 94-413). The Act established a multi-year project to demonstrate the economic and technological practicability of using electric and hybrid vehicles on the Nation's roads. The Act was conceived at the height of the Nation's first major energy crisis. The Act, as amended, provided for research and development projects, promulgation of vehicle performance and safety standards, a program of loan guarantees and small business planning grants, special studies, and other related activities. It also provided for vehicle demonstrations involving Federal, state and local governments, private citizens, and commercial/industrial organizations. Specific goals of the demonstration project were to:

- Demonstrate the economic and technological practicability of electric and hybrid vehicles for personal and commercial use,
- Promote the substitution of electric and hybrid vehicles for many gasoline and diesel-powered vehicles currently used in routine short-haul, low-load applications, and
- Facilitate the use of electric and hybrid vehicles in lieu of gasoline and diesel powered motor vehicles and develop recommendations for overcoming barriers to their use.

The authorized program was never fully funded by the Appropriations Committee. Activities were conducted in the period of 1976 to 1982. These activities were as follows:

- Opportunity and Risk Assessments (OPRA) - initially it is useful to conduct an assessment of opportunistic and risks which could be significant in achieving the program goals. The primary areas of concern are vehicle technology development, industry commercialization as influenced by incentives, user acceptance and market development, institutional barriers, organizational and policy decisions internal to the Federal Government and long term energy and environmental impacts,

- Marketing and Service demonstrations - conceived in order to test markets and to begin the development of an electric vehicle distribution and servicing infrastructure,
- Site Operators - programmatic operators were established throughout the USA to demonstrate the utility of electric vehicles,
- Test and Evaluation - site operators determined the technical and economic problems of operating fleets of electric vehicles, and
- Dealership Program - an attempt was made to establish electric and hybrid vehicle dealerships throughout the USA.

Aside from the benefits that might yet be achieved, the marketing and service demonstration programs did not achieve their objectives. The concept was a valid expression of Congressional objectives. However, because of an immature technology, an inadequate industrial commitment, a general slowdown in the Nation's economy, and unforeseen changes in energy economics and accompanying shifts in government policy, the program was terminated. While a modest level of activity in demonstrations could have been justified because of the feeling of urgency which pervaded the energy program environment in the mid 1970s, retrospective analysis shows that the dealership program was premature considering the circumstances which were emerging in the early 1980s.

Experience has determined that certain basic requirements should be applied to vehicle demonstrations. Companies producing the demonstration vehicles must have sufficient capital to cover start-up costs and maintain support through the initial deployment of the vehicle fleet. Demonstration fleets should be of sufficient size to allow for dedicated service personnel. It is important to the success of the demonstration that service personnel be given adequate technical training by vehicle manufacturers. Documentation and service procedures from the manufacturers must be complete and accurate. There must be provisions for spare parts in an efficient manner. Demonstration sites must be selected with compatible end-users in a variety of climates.

It is important to distinguish that the electric vehicle demonstration was a market demonstration. That is its goal was to effectively bootstrap an entire industry into existence. In order to achieve that goal, it included all phases of a prototype industry, including manufacturing, marketing, sale, and service. The goal also dictated a fairly large demonstration and well over a 1000 vehicles were involved. By contrast, for the Stirling engine, a more modest technology demonstration may be more appropriate. A technology demonstration involves about 50 to 100 vehicles. These vehicles are usually identical and concentrated in a small number of fleets, so that maintenance activities can be conducted by properly trained full time personnel. The vehicles can be assigned to different users to evaluate user reactions.

The technology demonstration concentrates on an evaluation of vehicle and subsystem performance, reliability, and cost in a semicontrolled environment. It does not attempt to create a prototype industry or to simulate actual free market conditions. The vehicles are assigned to trained personnel and subjected to periodic service and maintenance procedures to assure reliable operation.

The electric vehicle demonstration programs did provide an opportunity for "hands on" learning by electric vehicle manufacturers and users alike. The Site Operator program is still in existence, but on a smaller scale. This program has provided a steady stream of feedback from the end-users to the technology developers. This feedback resulted in identification and resolution of many technical deficiencies. The vehicles that are being produce today have benefited from this experience.

It should also be noted that we have available for your consideration documentation on many phases of the electric vehicle demonstration project. Some of the evaluation documents are attached. In addition, a complete project plan, requirements and guidelines for site operators, and sample operators' conference proceedings are available.

The above discussion should be helpful in defining our experience in the commercialization of vehicle systems. I hope this information and background are helpful to your efforts in Stirling commercialization. Please do not hesitate to contact me for any further information.

Sincerely,



Kenneth L. Heitner
Acting Manager, Test & Evaluation
Electric and Hybrid Propulsion Division

Enclosures

cc: Richard K. Shaltens
Stirling Technology Branch (MS 301-2)
Lewis Research Center
2100 Brookpark Road
Cleveland, Ohio 44135



Department of Energy
Washington, DC 20585

Mr. Richard K. Shaltens
NASA Lewis Research Center
MS 301-2 Stirling Technology Branch
21000 Brookpark Road
Cleveland, OH 44135

Dear Dick:

This is in response to your request for Department of Energy (DOE) input to your Inter-agency Stirling Commercialization Study. The response focuses on specific areas that you have designated for DOE participation.

ASE Program Assessment:

The accomplishments of the Automotive Stirling Engine (ASE) program have been significant. The Stirling engine technology at the beginning of the ASE program was at the stage of a laboratory curiosity. Today at the end of the ASE program the Stirling engine is operating reliably in real vehicles. Vehicle exhaust gas emissions, driveability, vehicle installation, engine manufacturability and projected cost have been established. This is a major accomplishment and NASA and the ASE contractors are credited with a job well done. As a result of the ASE program, a large technology base including designs for both Mod I and Mod II engines, engine component test data, engineering analyses, and detailed design requirements are available for industry's use in any further commercialization activities. It is the position of DOE that commercialization efforts focused on demonstrations with potential customers or for further product development should be supported solely by industry.

Potential Energy Benefits:

The data from engine dynamometer testing by Mechanical Technology, Inc. (MTI) support a 25%-30% improvement in vehicle fuel economy which would meet the original program goal. However, this has not been demonstrated in a Mod II powered vehicle system. The possibility exists that the Mod II engine could be malfunctioning but, there are no resources to perform the appropriate engine check out to verify that the engine is functioning properly.

United States Post Office (USPO) test results comparing the Environmental Protection Agency (EPA) combined cycle fuel economy for the Stirling versus the spark ignition showed a 4% to 6% improvement for the Stirling while it took 42% longer to accelerate to 55 MPH with the Stirling engine. The potential of the Stirling powered automobile to save a significant amount of energy or petroleum has not yet been demonstrated.

Alternative Fuels Projections:

The use of alternative fuels in place of petroleum derived fuels is a viable means of significantly reducing U.S. dependency on petroleum. The leading near term candidates, alcohols and natural gas are to a very limited extent already displacing petroleum derived fuels. For the longer term, it would be desirable to derive transportation fuels from abundant domestic resources such as coal and oil-shale, although those synthesis processes may have negative greenhouse gas impacts. These resources can be processed into a variety of hydrocarbon fuels similar to gasoline and diesel fuel and into oxygenates such as methanol. However, present high production costs hinder their widespread acceptance. There is much renewed interest currently on alternative fuels for potential air quality benefits. DOE efforts in this area are attempting to insure that inadequate utilization technology is not a barrier to the widespread use of fuels which can be derived from our long term resources.

The Department has been conducting research programs for over a dozen years to develop fuels which are acceptable to the marketplace with regards to availability, cost, and environmental impacts. Many problems concerning utilization of methanol have been resolved to the extent that first-generation flexible-fuel light-duty vehicles are in production. For heavy duty engines, the technology is considerably less developed although new diesel engines emissions requirements have made methanol an attractive alternative fuel candidate. Heavy-duty natural gas engines are also the subject of renewed interest for reducing air pollution. Natural gas, which is primarily methane, appears to offer excellent qualities, including abundant sources and possible reductions in exhaust emissions. One disadvantage, however, is lower energy content and hence reduced driving range compared to other fuel options. The near future of natural gas, (as compressed natural gas), appears most promising to fleet operations and buses where these restrictions are of less concern.

It is generally accepted that the external combustion in the Stirling will allow more flexibility to accommodate alternative fuels. However, it appears that the fuels that are likely to become dominant are compatible with existing engines as a prerequisite. These alternative fuels do not appear to generate a demand for the Stirling engine.

Future Energy Assessment:

The Department predicts net petroleum imports of crude oil and refined products will increase from 6.3 million barrels per day in 1988 to 10.2 million barrels per day in 2000. The forecast for 2000 reflects the net imports divided by total petroleum demand of 55 percent up from 37 percent in 1988. Most of the projected future increase for petroleum demand is for industrial and farm diesel and jet fuel, but not for gasoline (thanks to increasing auto fuel efficiency). Gasoline price is predicted to increase very little between now and the year 2000.

Improved fuel economy will continue to be a priority from a national point of view, especially with the desire to lower CO₂ production. Fuel cost, however, is becoming a smaller fraction of overall cost of the automobile and the consumer is growing less interested in the importance of fuel economy. The effect of these factors is that the Federal Government will have to exert an increasing influence to cause more fuel efficient engines to be developed.

Future Engine Projections:

A recent assessment of near-term technological improvements to automobiles to improve fuel economy has been performed under sponsorship of the Department of Energy, Office of Policy Integration. While endorsed by neither the Government nor industry at this time, it does represent an up-to-date evaluation of the potential for near term technical improvement in the auto industry. The following information is drawn from the assessment.

Two of the most important changes in engine technology are the shift to overhead camshaft (OHC) engines and the incorporation of 4-valve technology. Both Ford and GM are planning the introduction of a variety of OHC engines in the 1991-1994 time frame while Chrysler was already utilizing OHC engines in the majority of its 1987 fleet. All manufacturers will also introduce 4-valve/cylinder technology in a variety of 4, 6, and 8-cylinder engine models but it is anticipated that both the 4-valve and 2-valve versions will be sold with the former as an option. A near 100 percent transition to OHC is expected to occur by 2000 in cars. In Light Duty Trucks (LDT's) it is estimated that the introduction of OHC engines will lag their introduction in cars by 4 to 5 years, and overhead valve engines will continue to predominate in the full-size models even in 2000. The use of 4-valve technology will be limited to compact LDT's. However, it is anticipated that 3-valve single overhead cam engines are likely to be used in the standard size pickup trucks by 2001.

Engine friction reduction will occur by the use of roller cam followers (these were adopted in many engines in 1988/1989, while several engine models incorporated them as early as 1985) and the use of low mass pistons and rods coupled with low tension piston rings. The latter technology was used in some engines in 1986 and 1987, but further evolutionary improvements in friction reduction are expected by 1995 and again by 2001. The use of on-center bores in the 90 degree v-6 engine from GM also provides some additional improvement in fuel economy in 1988/1989. These technologies will also see universal use in the LDT fleet by 2001.

Increased use of fuel injection has already occurred in 1988/1989, but gradual transition from throttle body fuel injection to multiport fuel injection will occur in the 1990-1995 time frame. (This will, in part, be driven by the emission standards and other emission related regulations). In the post-1995 time frame, variable valve timing is expected to be used on many (if not all) 4-valve engines employing double overhead camshafts (DOHC). Turbocharging and supercharging will be offered in a few sporty model cars but their widespread use is not foreseen. The following fuel economy gains for these technologies are predicted to be realized by the year 2000: overhead camshaft - 6%, roller cam followers - 1.5%, low friction pistons/rings - 2%, multiport fuel injection over throttle body fuel injection - 10%.

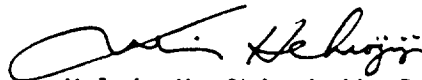
As the fuel economy of the spark ignition continues to improve and as fuel cost becomes a smaller part of automobile total life cycle cost, it is becoming more difficult to justify the industry investment required to tool up, produce and support a new engine like the Stirling.

Past Fleet Demonstrations:

This subject is addressed in a letter to Lennard Ault dated January 17, 1990, in which Kenneth Heitner of this office discusses the DOE experience with Electric vehicle demonstrations.

The opportunity to participate with NASA and the other agencies on this study is very much appreciated. If there is anything in addition, that we can do to assist you in the preparation of your report to Congress, please don't hesitate to call me.

Sincerely,

A handwritten signature in black ink, appearing to read 'Melvin H. Chiogioji', is written above the typed name.

Melvin H. Chiogioji, Director
Office of Transportation System
Conservation and Renewable Energy

cc: Lennard Ault, NASA TU



U.S. Department
of Transportation

Urban Mass
Transportation
Administration

Headquarters

400 7th Street S.W.
Washington, D.C. 20590

Mr. Leonard A. Ault
Acting Director
Technology Utilization Division
National Aeronautics and
Space Administration
Washington, DC 20590

JAN 31 1990

Dear Mr. Ault:

I enjoyed participating in the meetings on the commercialization study of the Stirling Engine. I believe that the Stirling Engine is a potential engine alternative to compressed natural gas, methanol, and other alternative fueled engines being considered by the transit industry to meet the Environmental Protection Agency's (EPA) 1991 particulate emissions requirement for transit buses. The multi-fuel capability of the Stirling Engine makes the transit agencies less dependent on diesel fuel sources.

These benefits can only be obtained if the Stirling Engine can be developed for transit buses, meet the 1991 EPA particulate emissions requirements of 0.10 grams per brake-horsepower for transit buses, and be cost competitive with other engine technologies.

Although the technical feasibility of the Stirling Engine technology has been demonstrated, we believe it is not ready for transit use. Extensive development and testing work are required before transit agencies would accept or consider to purchase buses outfitted with Stirling Engines. The most appropriate applications would be small carefully controlled demonstrations where proper technical support and evaluation personnel can be provided by the developer. If you have any questions regarding our position of the Stirling Engine please contact me at 202-366-0220.

Sincerely,

George I. Izumi
Program Manager



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

ANN ARBOR, MICHIGAN 48105

JAN 16 1980

OFFICE OF
AIR AND RADIATION

Mr. Richard Shaltens
MS 301-2
NASA Lewis
21000 Brookpark Road
Cleveland, OH 44135

Dear Mr. Shaltens:

Based on our recent telephone conversation, I understand that you are interested in what emission requirements vehicles powered by Stirling engines will have to meet.

The emission standards that future vehicles will be required to meet are the subject of Congressional debate as I write this letter. Therefore, the best guidance that I can give you is a range. The range of Federal requirements is taken from the enclosed paper that summarizes current proposals in its Table 1. The California requirements are those currently under consideration for the future.

In your study of the Stirling engine, don't fall into the trap of considering only exhaust emissions. As the enclosed paper clearly indicates, emissions other than exhaust emissions may be the more important part of the future emissions picture as far as the volatile organic emissions go. The emissions of these hydrocarbons are a strong function of the fuel used and the control system used. Most of the work done to date with alternative engines (including the Stirling) has ignored this, so the prototype vehicles that currently exist would all probably fail badly in meeting stringent evaporative, refueling, and running loss standards.

Also don't forget particulate emissions. If you use a distillate-type fuel, like those with which much Stirling engine development has been conducted, you will need to look at particulate emissions too.

Another aspect for the future is alternative-fuel capability. The candidates are: natural gas, ethanol, methanol, LPG, and reformulated gasoline. Engines that can use all of the fuels clearly and efficiently may rank higher.


If you try to compute emission results using burner rig data, emission index (g/kg fuel) results, and fuel consumption, please caveat the results extensively. Thermal and speed/load transients are very important for low emissions and not much burner data exists for those operating modes. When using the burner rig data fabrication approach, don't forget the Stirling engine warm-up time. As clearly pointed out by Amann in SAE Paper 891666, the burner operates, consumes fuel, and pollutes while the heater head is coming up to temperature, and fuel and emissions also have to be accounted for.

The range of future Federal standards can be obtained from the enclosure. California is considering non-methane hydrocarbon requirements of 0.125 grams per mile, 0.075 grams per mile, and 0.040 grams per mile. California basically has a 0.015 grams per mile formaldehyde standard also.

With respect to particulates, I'm estimating that something in the range of 0.20 grams per mile (the current Federal range) to 0.08 grams per mile, California's requirement, will be the numbers to consider.

Good luck on your study. If you can drop by our lab when you visit Ford and GM, please let us know.

Sincerely yours,



Karl H. Hellman, Chief
Control Technology and Applications Branch

Enclosure

cc: G. Piotrowski, CTAB (w/o enc)



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

ANN ARBOR, MICHIGAN 48105

29

Mr. Richard Shaltens
MS 301-2
NASA Lewis
21000 Brookpark Road
Cleveland, OH 44135

OFFICE OF
AIR AND RADIATION

Dear Mr. Shaltens:

We enjoyed meeting with you on Wednesday, January 24, 1990. It looks like you have a lot of work to do in a short amount of time in preparing your report on the Stirling engine.

With respect to the requirements that vehicles equipped with Stirling engines may have to meet in the future, I strongly urge that you stress the moving baseline and the possible range of future requirements.

The Moving Baseline

The competition keeps improving. Cars powered by conventional engines keep getting more efficient and cleaner. The real test for alternatives to current powerplants is not whether they are projected to be better in some measure than today's or yesterday's vehicles, but whether they are projected to be better than today's engines are projected to be. This necessarily leads to some degree of speculation (projection versus projection), but it appears to me to be the fairest way to compare.

Range of Requirements

Today's fleet MPG standard is 27.5. Values in the low 30's are being discussed for the mid-1990's, and higher values are being considered for future years. My guess is that the requirements will range as follows:

<u>Year</u>	<u>Effective MPG Requirement</u>
1990	27.5
1995-97	27.5 to 35
2005	27.5 to 40
2015	27.5 to 50

The pros and cons of the Stirling may be different depending on which end of the range you consider.

I already sent you materials that will allow you to construct ranges for future exhaust emission requirements.

FEB 8 1990

Emission Durability

There are two jobs to accomplish before one can say that there is a high probability that any emission standard can be met: 1) low-mileage emission achievement and 2) durability demonstration. Meeting the level of an emission standard at low mileage is a necessary but not sufficient condition.

The data that I have seen so far from vehicles powered by Stirling engines are totally deficient with respect to any evaluation of evaporative emissions, either diurnal emissions or hot-soak losses. As you can tell from the information I sent you, emissions other than exhaust emissions are much more important than they used to be.

With respect to exhaust emissions, the scattered bits of data I have seen indicate that the emission levels measured at low mileage are about the same, maybe even somewhat higher than those measured from today's cars at low mileage. Please see the enclosed test car lists for the model years you requested for the details.

The biggest unknown is durability. Low emissions have to be maintained for the length of the durability requirement. If the requirement is for a passenger car the durability requirement is 50,000 miles. If the vehicle is a light-duty truck the requirement is much longer. I've used 120,000 miles in the example below. To remove variability, you really need to run multiple vehicles and have multiple tests at each test point (each 5,000 miles). A test costs about \$2,000 and it can cost about \$2 per mile to have the miles put on. You said that each test car would cost \$500,000. For a three-vehicle program the costs are estimated below.

Costs to Run Durability Three-Vehicle Program

	<u>50K Durability</u>	<u>120K Durability</u>
Vehicle cost	1500K	1500K
Mileage cost	300K	720K
Test cost	180K	432K
TOTAL	1980K	2652K

It looks to me like you need about 2 to 3 million dollars to get a handle on emission durability for a single well-defined package with low-emission potential.

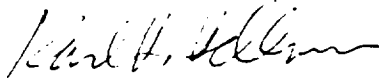
I've included some information about recent air quality measurements. These data indicate what I told you in the meeting, that there is a substantial ozone and carbon monoxide air quality problem in the U.S.

Also included is SAE Paper 835023 by T. Weber. If you could send us a copy of the work you mentioned that NASA has done on hydraulic hybrids, we would certainly appreciate it.

Finally, while an efficient, clean low-power engine for a hybrid is quite attractive (the ghost of the Stirlec?) and the 250K value you cited is attractive as research equipment goes, it seems that the engine you have under development is solar-powered not combustion gas powered, as I understood you to say, and so doesn't fit in with our current plans. If you develop a propulsion system with hydraulic launch capability that could operate cleanly on alternate fuels, we would of course be more interested.

Good luck with your study. We would appreciate seeing a draft of it, at least the sections that deal with emissions. If Jack McFadden is assisting you with this, have him give me a call if he has any questions about the CFR booklets we've included.

Sincerely yours,



Karl H. Hellman, Chief
Control Technology and Applications Branch

Enclosures

cc: G. Piotrowski, CTAB (w/o enc)

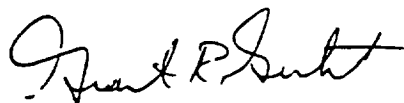
6 MAR 1990

AMSTA-RSA

MEMORANDUM FOR: NASA Lewis Research Center, Stirling Technology Branch,
Mail Stop 301-2, Mr. Richard Shaltens, 21000 Brook Park Rd., Cleveland,
Ohio, 44135

SUBJECT: Summary of Infrared (IR) Testing of a Stirling Engine Pickup
Truck

1. Subject testing was conducted at The U.S. Army Tank Automotive Command, Warren, MI on the morning of 6 Dec 1988. IR imagery was used to compare the signature of the Stirling pickup and a conventional V-8 Dodge D-150 pickup.
2. The Stirling pickup exhibited a much lower exterior signature during identical warmup and operational tests. Heating of the engine compartment exterior was greatly reduced for frontal, side, and top viewing. An example of this effect was the frontal left exterior reduction from 18.5 degrees Centigrade (C) on the V-8 pickup to 12.7 degrees C on the Stirling pickup. The exhaust pipe temperature was reduced from 66 degrees C to 22 degrees C from side viewing angles. Heating of the ground under the Stirling pickup was also significantly reduced.
3. Imagery of the open engine compartment areas on the two pickups provided the source of the external signature differences. The internal combustion engine had significant radiant heat losses from the exposed exhaust manifolds which were at a 285 degree C temperature. The maximum temperature of the Stirling engine exterior was 47 degree C, except for the a very small area above the ignitor which measured 285 degrees C, and the exhaust manifold was 45 degrees C.
3. In summary, the Stirling pickup exhibited much lower IR signature levels during testing. This appeared due to the high efficiency and low heat rejection levels of the engine compared to conventional pickup engines. The low IR signature of the engine would be ideal for applications in light wheeled vehicles for transport of forward observers. Signature suppression hardware could be used to reduce the IR signature to levels below conventionally powered wheeled vehicles. Another application would be in low signature auxiliary power units (APU's) for military applications. This type of engine could also be used in heavy combat vehicle applications to reduce inherent IR signature levels.
4. The POC on this test evaluation is Mr. Wally Mick, of the Applied Research Branch, AMSTA-RSA, telephone number 313-574-8911 or AV786-8911.



GRANT R. GERHART
C, Applied Research Br

JAN 3 1990

Mr. Leonard Ault
Acting Director, Technology Utilization
National Aeronautics and Space Administration
Washington, DC 20546-0001

Dear Mr. Ault:

I have read your letter regarding the commercialization study of Stirling Engine Technology requested by Congress and offer the following comments.

Robert K. St. Francis, Director, Office of Fleet Management, U.S. Postal Service, is the Postal Service's representative for this study. He can speak for the Postal Service on this program.

Approximately two years ago, the U.S. Postal Service was approached by NASA to participate in a demonstration project because of our unique vehicle operational environment. We in turn volunteered to participate in this program as a test bed or test platform and gather operational data pertaining to the performance of the vehicle with a stirling engine compared to that of a conventional spark ignited internal combustion engine. The preliminary results are available and our assessment shows that the engine performs less favorably than the original engine furnished with the vehicle. While I recognize that the stirling engine is in its development infancy for automotive application, I can not envision any potential long term benefits for the Postal Service or any large scale application to our fleet operation.

In response to the three points raised in your letter, the following responses are presented.

Point 1. Long term sponsor

Response: The mission of the Postal Service is to provide a uniform, universal delivery system to the nation. Our role is not to develop engine technology for future automotive applications. We would, as we have in the past, participate in a limited demonstration project if requested, providing it did not interfere with the efficiencies of our mail delivery system. We would not be a long term sponsor.

Point 2. Agency cost sharing

Response: The Postal Service would absorb the costs associated with a limited demonstration test as we presently have done, again with the proviso that the demonstration would not adversely effect our delivery capability.

Point 3. Agreement on the key study results and recommendations

Response: This is difficult for me to comment on because of the many technological variables involved. If the engine is operating, as I have been told, and producing less emissions in some areas and may be capable of running on many alternative fuels, can a consensus be reached that this is the ultimate engine for future automotive application? I do not think so. The engine technology (stirling) is in its modern day infancy even though the concept has been around a long time. For me to predict that an agreement be reached on a complex subject such as this is premature and should be determined by the deliberations of your study group. There exists a possibility that many differing opinions may come out of these deliberations, and all of them should be reported objectively to Congress.

If I can be of any further assistance, please feel free to contact me.

Sincerely,

 Arthur Porwick
Assistant Postmaster General



UNITED STATES POSTAL SERVICE
475 L'Enfant Plaza, SW
Washington, DC 20260

FEB 21 1990

Mr. Len Ault
Director of Technology Utilization
National Aeronautics & Space Administration
Code CU
Washington, DC 20546-0001

Dear Mr. Ault:

The evaluation of the second generation automotive Stirling Engine (Mod II ASE) powered Long Life Vehicle (LLV) by the USPS was concluded on December 29, 1989. We appreciated the opportunity to participate in this evaluation. The Stirling Engine powered LLV arrived at the USPS Engineering & Development Center on September 29, 1989 and our evaluation continued for approximately three months.

We encountered various engine/accessory problems and a chase vehicle was needed throughout the evaluation period. As a result of these problems, it appears that this engine is still in the development prototype stage and is not ready for larger fleet deployment until the problems can be resolved and the chase vehicle can be eliminated.

EPA Urban Cycle Fuel Consumption Test results showed that the present GM 2.5L IC Engine LLV had a 3% to 4% better fuel economy than the Stirling Engine LLV. For the highway cycle, the Stirling Engine LLV had a 18% to 23% better fuel economy than the GM 2.5L IC Engine LLV. However, it should be noted that the USPS usage of this vehicle is very similar to the urban cycle. On the actual Postal delivery route, the Stirling powered LLV consumed 38.5% more fuel than the GM 2.5L IC Engine. Therefore, we conclude that the present Mod II Stirling Engine is not suitable for Postal operation.

A more detailed analysis of the performance of the vehicle is included in the "Stirling Engine Powered Long Life Vehicle Evaluation Program Final Report" which is attached.

If you have any question, please contact me at 268-3615 or John Bowen at 641-7130.

Robert St. Francis
Director
Office of Fleet Management

cc: Albert Chesnes, Department of Energy
Albert Ritchey, MTI

APPENDIX I

STIRLING COMMERCIALIZATION STUDY:
INTERAGENCY PARTICIPATION

In response to House Report 101-226 accompanying HB 1759, the National Aeronautics and Space Administration Multiyear Authorization Act of 1989, NASA Headquarters, Office for Commercial Programs, Washington, DC, requested the NASA Lewis Research Center, Cleveland, Ohio, because of their extensive research efforts in support of the automotive Stirling engine technology, to take the lead in conducting the study for Congress.

The report language directed NASA to request participation from other Federal agencies and encouraged NASA to consult with the private sector. An interagency study team was formed as requested and the private sector was consulted.

The first meeting of the interagency study team was held on December 7, 1989, in Washington, DC. Agencies represented in addition to NASA were the Department of Energy, the Department of Transportation, the Environmental Protection Agency, the United States Air Force, and the United States Postal Service. At this meeting NASA reviewed with the attendees the congressional report language directing the study, the background and status of the DOE Automotive Stirling Engine (ASE) Program, the background on Stirling engines, and a plan to respond to Congress. Potential areas of participation were also reviewed and discussed with the various agencies. A second meeting of the interagency study team was held on January 4, 1990, in Washington, DC. Areas of expertise and participation were discussed with the agencies, and key areas of participation were identified for each agency as follows:

DOE

- Potential energy benefits
- ASE program assessment
- Past fleet demonstration experience
- Alternative fuels projections
- Future energy assessment
- Future engine projections

EPA

- Potential and current emission benefits

- Current emissions standards and engine capability
- Future emissions standards and engine capability

DOT

- Potential urban mass transport benefits
- Past fleet demonstration experience

NASA

- Lead for interagency study
- Stirling technology assessment
- Consultation with private sector
- Other duties as required

Air Force, Army, and USPS

- Potential benefits
- Recommendation of demonstration fleet
- Stirling demonstration results

Further potential Stirling benefits for the automotive application were reviewed and discussed with personnel from the attending agencies. Each agency was requested to provide written comments reflecting its input in its areas of expertise.

In consulting with the private sector, visits were made and discussions held with key personnel familiar with the DOE ASE program from the following industry organizations, who were:

1. Cummins Engine Company, Columbus, Indiana
2. Deere & Company, Moline, Illinois
3. Ford Motor Company, Dearborn, Michigan
4. Gas Research Institute, Chicago, Illinois
5. General Motors Research Laboratories, Warren, Michigan
6. Hercules Engine Incorporated, Canton, Ohio
7. Kennedy Engine Company, Biloxi, Mississippi
8. Stirling Thermal Motors, Inc., Ann Arbor, Michigan

Each organization was sent 10 "Questions for Industry" (attachment 1) prior to the visit to serve as a basis for discussing potential Stirling commercialization efforts. Written responses were received from all the organizations except Hercules and Stirling Thermal Motors. A visit was also made to the EPA, Ann Arbor, Michigan, for an in-depth review and discussion of both current and future automotive emissions standards.

In addition, a visit was made to the DOE ASE program contractor (Mechanical Technology Inc., Latham, New York) to obtain the current status of the NASA ASE project. MTI was very cooperative throughout the study and has provided the necessary information and data to NASA when requested.

NASA has prepared the Stirling commercialization study report based on the following:

1. Discussions with the industry organizations and their written responses
2. Discussions with the interagency participants and their written responses in their areas of expertise

Questions for Industry

1. What advantages do you see for the Stirling engine that make it attractive to you as a manufacturer?
2. What are the disadvantages or shortcomings of Stirling that might discourage you from manufacturing Stirling engines?
3. What technology barriers do you believe exist for the Stirling?
4. What are the market needs for a new type of engine such as Stirling?
5. What market barriers exist for a new type of engine such as Stirling?
6. What do you see as the initial application(s) and market(s) for the Stirling engine?
 - Application(s) and engine size(s)?
 - Initial market sizes and initial engine cost?
 - Initial production run and mature engine cost?
 - How many years before mature market production? Annual production?
7. Describe a demonstration program that you would require before entering into initial production of a new type of engine such as Stirling?
 - Number of engines?
 - Type of testing?
 - Component and system performance
 - Endurance or life and reliability
 - In-service evaluations
8. What is your estimate (timetable) to bring a new engine such as Stirling into production?
 - _____ years for the design and development?
 - _____ years to demonstrate performance? endurance? _____ size?
 - _____ years for in-service evaluations? _____ size?
 - _____ years to initial production? _____ size? Plant cost?
 - _____ years to mature production? _____ size? Plant cost?
9. What is government's role in the commercialization of a new engine such as Stirling? Why?
10. Considering the advantages attributed to Stirling and the progress made in advancing Stirling technology, why has industry not been interested in pursuing it?